Nano Mechanical Array Signal Processor Program (NMASP)

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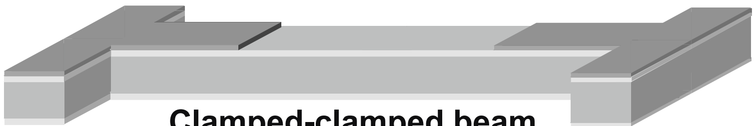
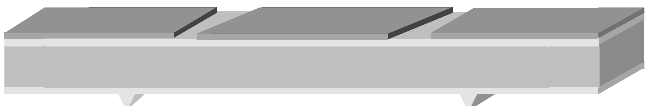
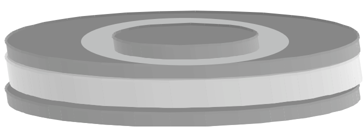
Nano-Mechanical Array Signal Processor Program



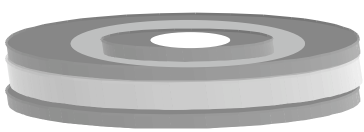
Clamped-clamped beam



Free-free beam



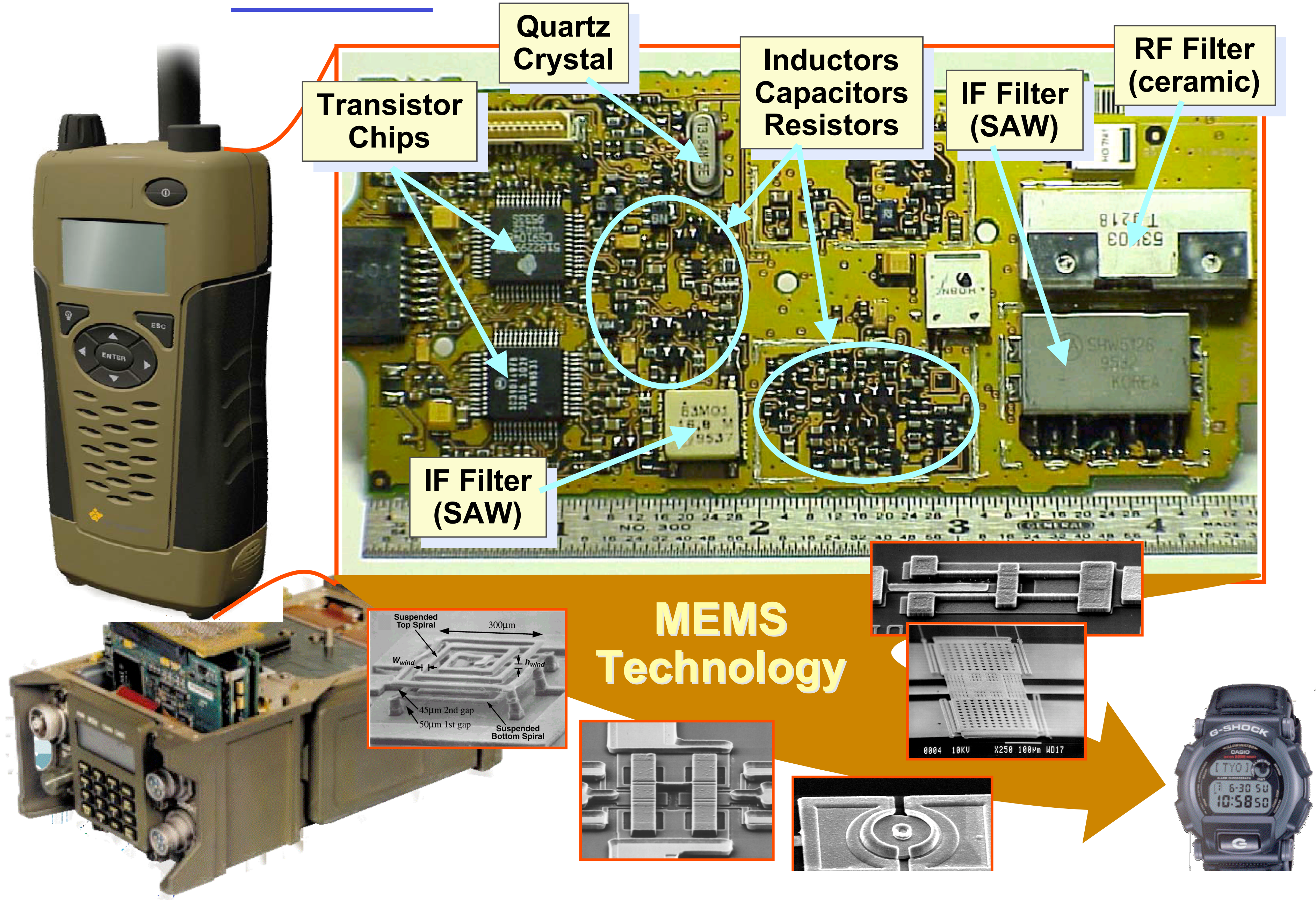
Fixed-free disk



Fixed-free-free annulus

- **Goal:** Create technology for arrays of precision, high Q, nano mechanical resonators and structures for RF-signal processing (up to 1GHz).
- **Challenges:** Nano-scale precision fabrication, efficient coupling and transduction mechanisms, overcoming loss mechanisms.

MEMS Provides Size Reduction



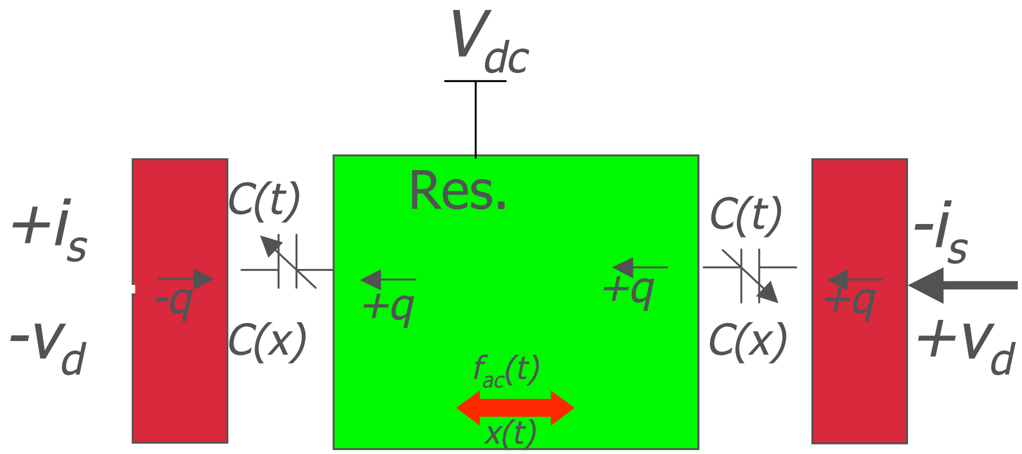
NMASP

- Motivation for Program
  - Enable >100X reduction in size & power consumption & 10X improvement in performance for UHF wireless communication.
- Military Impacts
  - The development of NMASP will enable ultra miniaturized (wristwatch or hearing aid in size) and ultra low power UHF communicators/GPS receivers. Their uses can greatly improve the mobility and location identification of individual war fighters, as well as standalone wireless sensor clusters.

NMASP

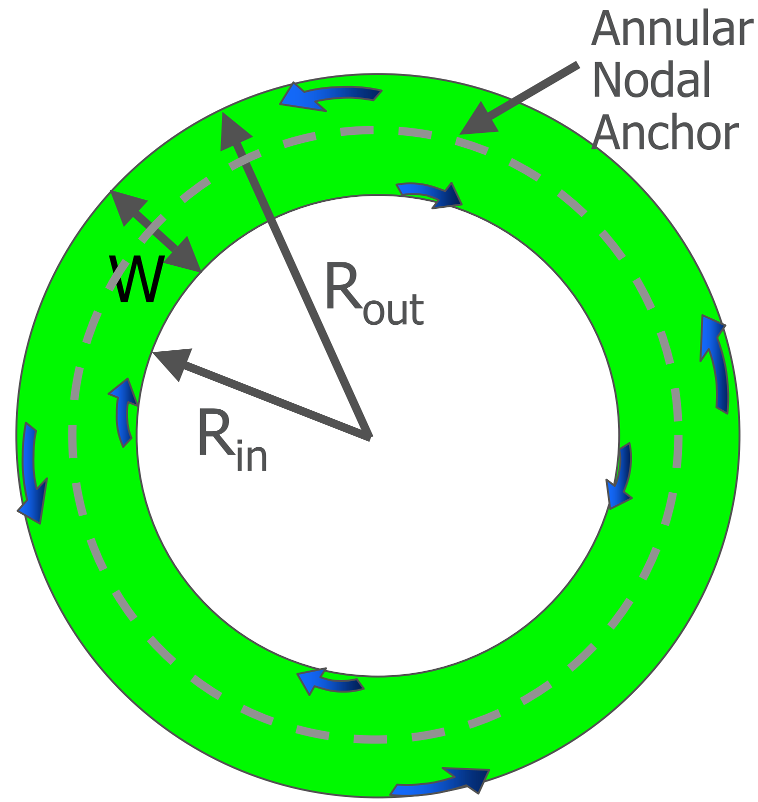
- Start Date: 2001 End Date: 2004
- Program Status: On-Going
  - Precision in material growth technology attained
  - Working on methods for coupling resonators
  - Scaling up arrays of devices
  - Aiming to have some demo’s later this year

Principles of Mechanical Resonators



$$f_{ac} = v_{ac} \cdot V_{dc} \cdot \frac{2C_0}{gap}\left(1 + \frac{3x^2}{gap^2}\right)$$

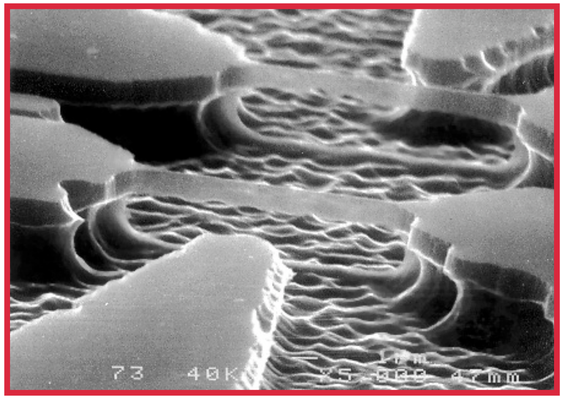
$$i_{sense} = X \cdot \omega \cdot V_{dc} \cdot \frac{2C_0}{gap}\left(1 + \frac{3x^2}{gap^2}\right)$$



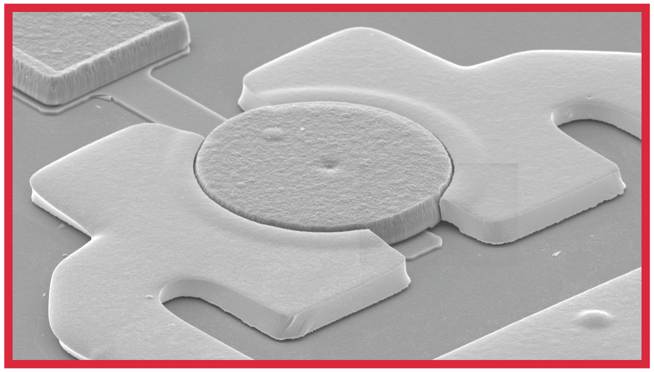
$$f_{SRR} = \frac{1}{2(R_{out} - R_{in})}\sqrt{\frac{G}{\rho}} = \frac{1}{2W}\sqrt{\frac{G}{\rho}}$$

Nanomechanics and Resonators

- SAW/BAW filters are current state-of-art
  - Resonant frequency strong function of material thickness
  - Large devices, separately packaged
- MEMS processes offer ability to fabricate resonant beams and structures
  - High resonant frequencies with low force constants (f goes as W/L^2)
  - Small length, width, but also small gaps (R goes as gap^4)



Caltech 330 nm-wide twin resonators (f_0 = 70.7 MHz, Q = 20,000)

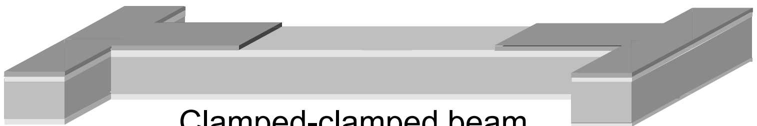


U. Michigan radial polysilicon f_o ~ 200 MHz, Q ~20,000

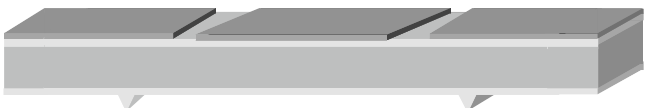
Why Nano-Resonator Filters?

- Integrated resonators that implement high-*Q* filter functions with *huge* reductions in power and volume
- Arrays of resonators that allow analog spectrum generation and analysis
- Enable new transmitter and receiver architectures: *secure, ultra-low power, multi-standard communications!*

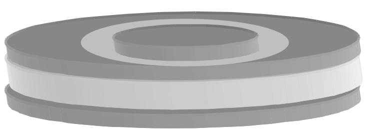
Resonator Topologies



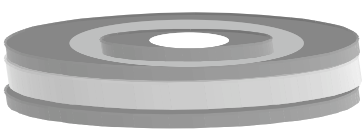
Clamped-clamped beam



Free-free beam

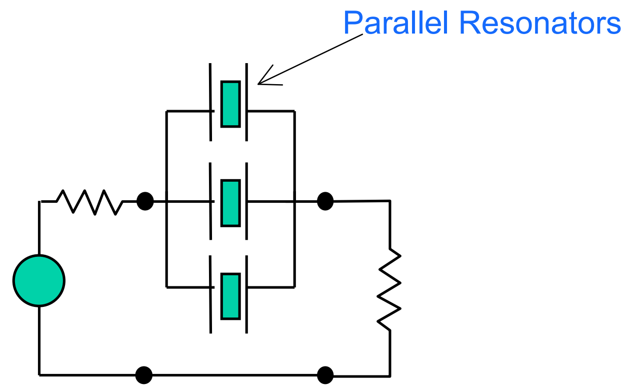


Fixed-free disk

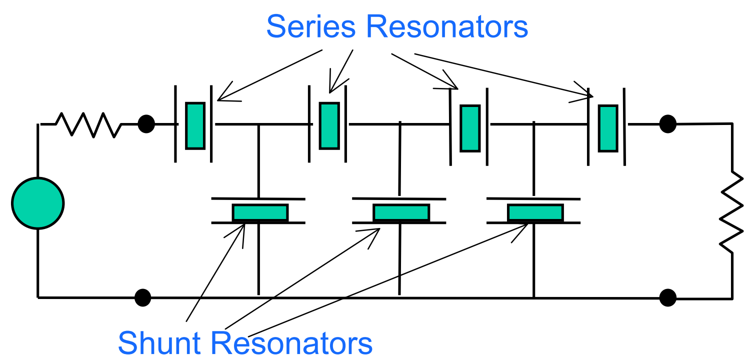


Fixed-free-free annulus

Filter Topologies



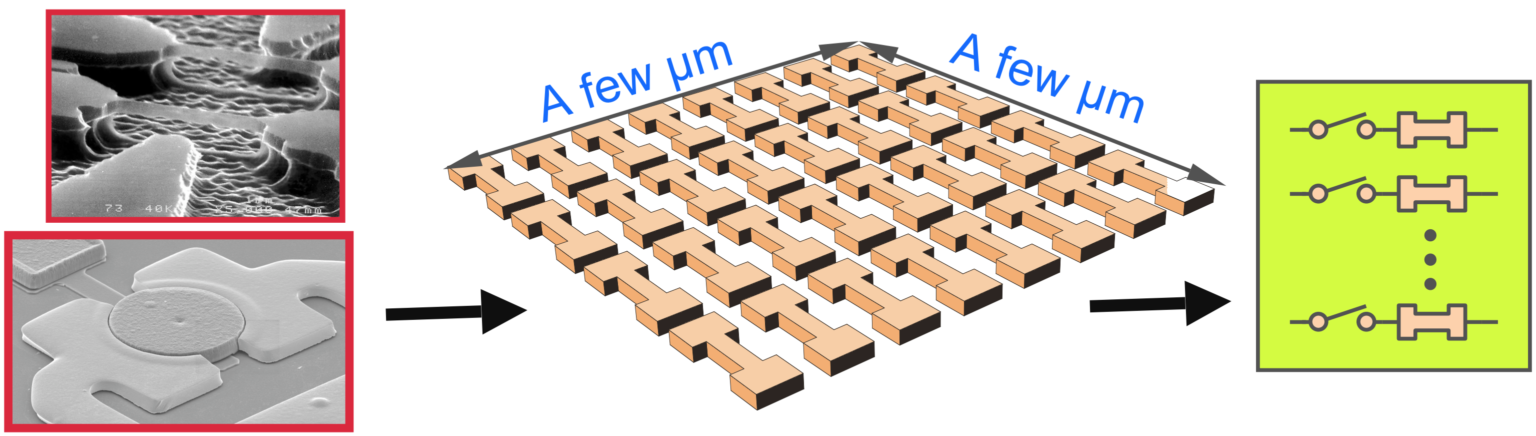
Parallel circuit



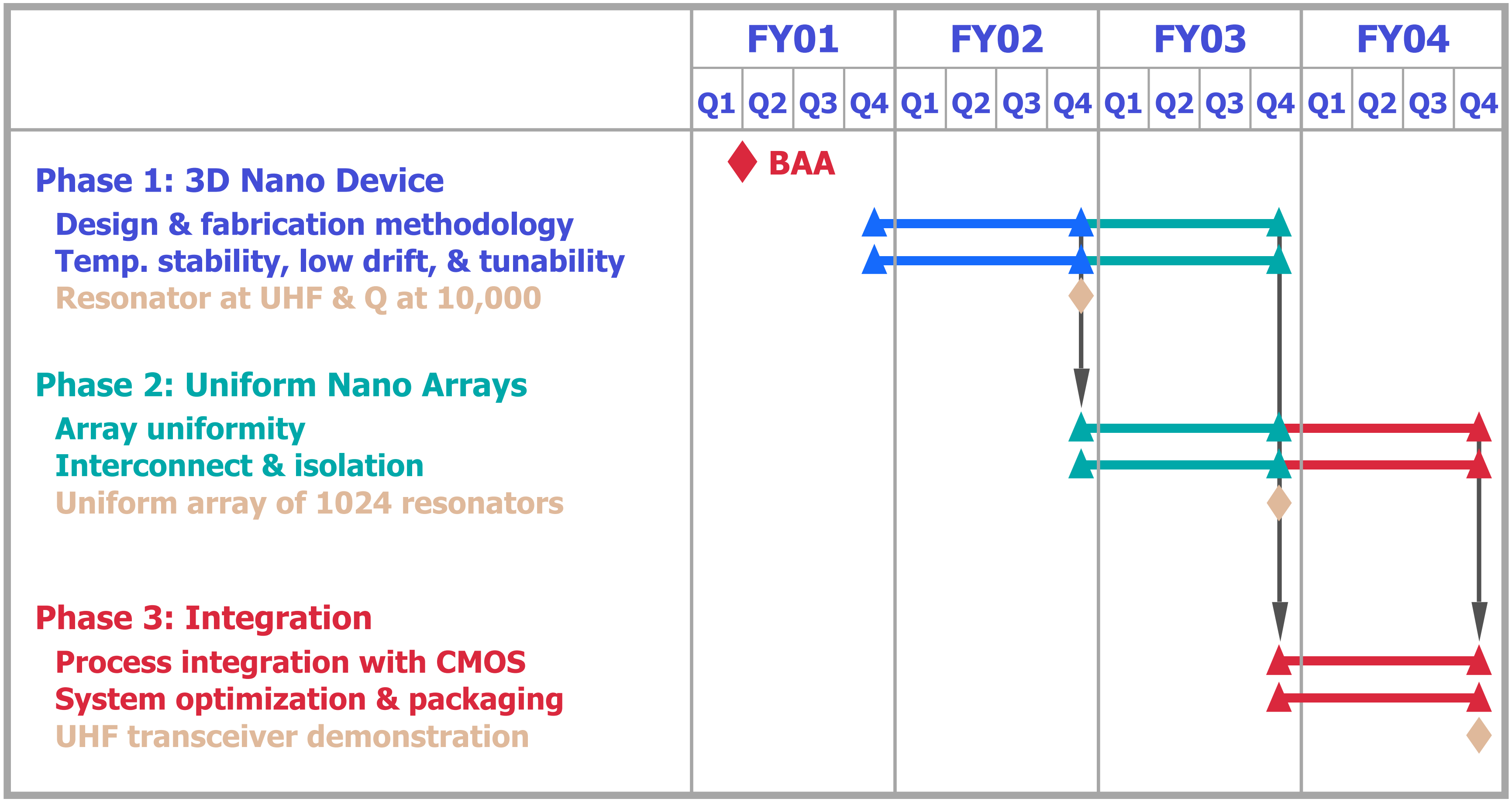
Ladder circuit

Approach

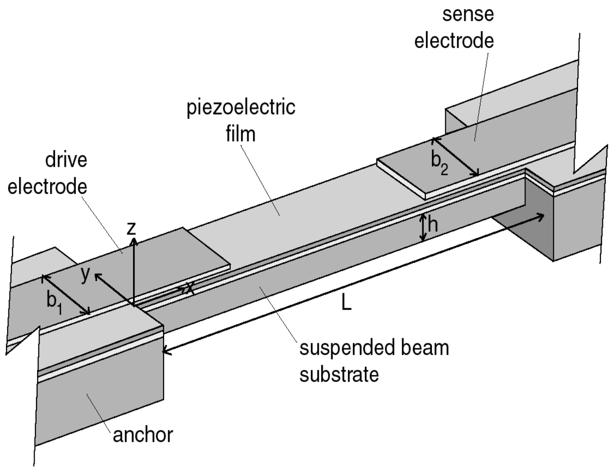
- Silicon-based process technologies (GA Tech, Michigan, CMU, UCB)
- Piezoelectric (U. MD/Northrop, Honeywell, JPL, Draper, HRL, UCSB)
- Carbon Nanotubes (JPL/Brown, UCI)
- Arrays and Interconnections
- RF Architectures

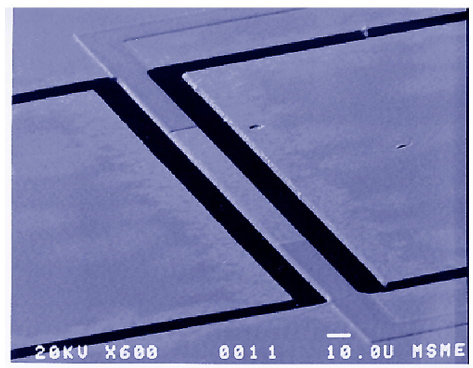


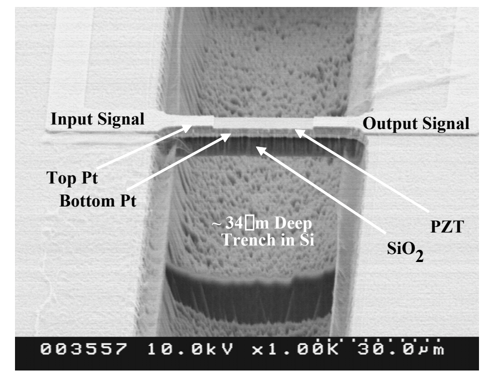
NMASP Program Schedule



Piezoelectric Resonators







- ZnO and PZT resonators demonstrated (UMd)
- Unsatisfactory performance due to poor Q and ultimate frequency limits

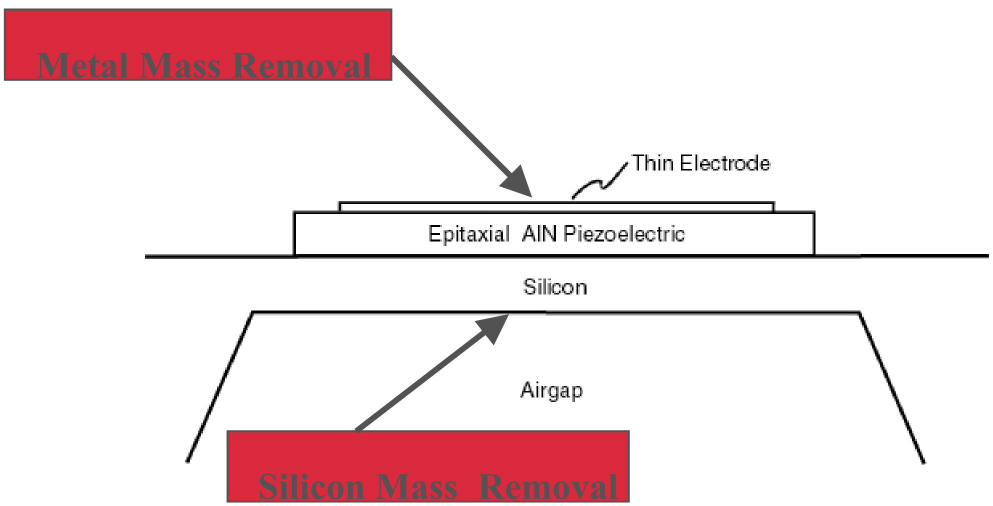
- **Good electromechanical scaling to microwave frequencies (□$^{-1/2}$ for piezoelectric vs □$^{-5/2}$ for capacitive)**
- **Good microfabrication scaling (strain-based vs. displacement-based)**
- **Low-voltage operation (CMOS levels and below)**

Why AlN? AlGaAs?

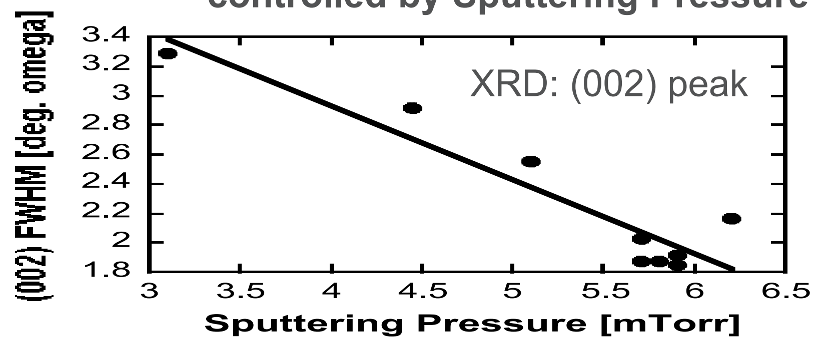
	AlN	$Al_{0.3}Ga_{0.7}As$	GaN	BN
$\square_{11}$ [m/s]	11270	4934	7900	15400
K^2 (d_{31} mode)	0.26	0.02	0.02	0.16
$\square_r$	9.14	12.0	9.7	7.1

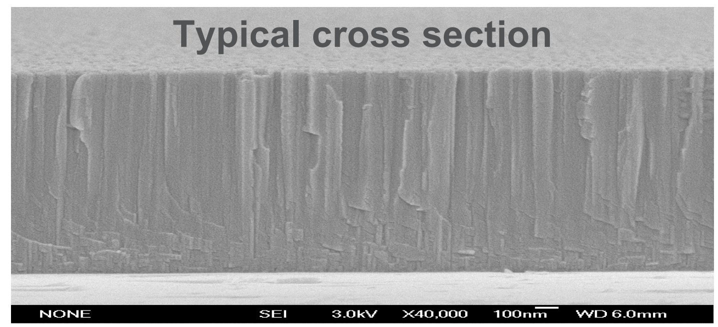
- AlN:
  - Excellent figures of merit
  - Strong potential for near-term discrete-chip filters
- AlGaAs:
  - Lower figures of merit, but:
  - Well characterized epitaxial processing for high quality single-xtal films
  - Integration with high-speed electronics and optoelectronics
  - Directly implementable in standard HEMT processes

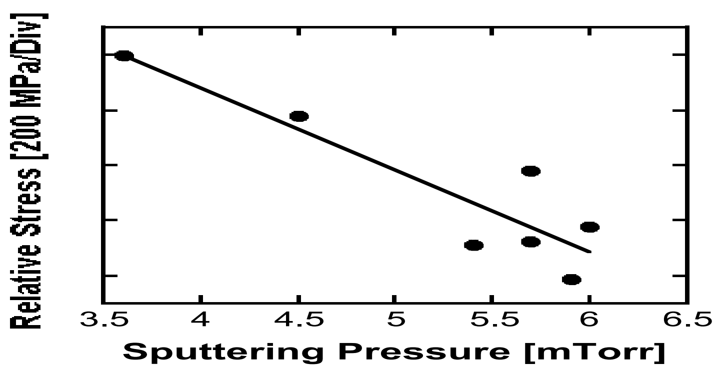
NMASP Materials: AlN on Silicon

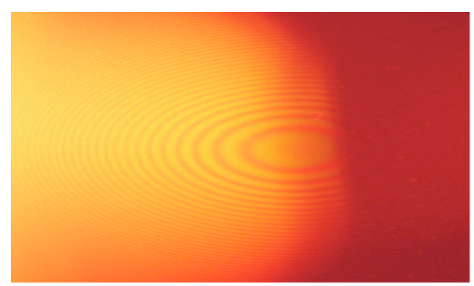


Crystalline Orientation controlled by Sputtering Pressure



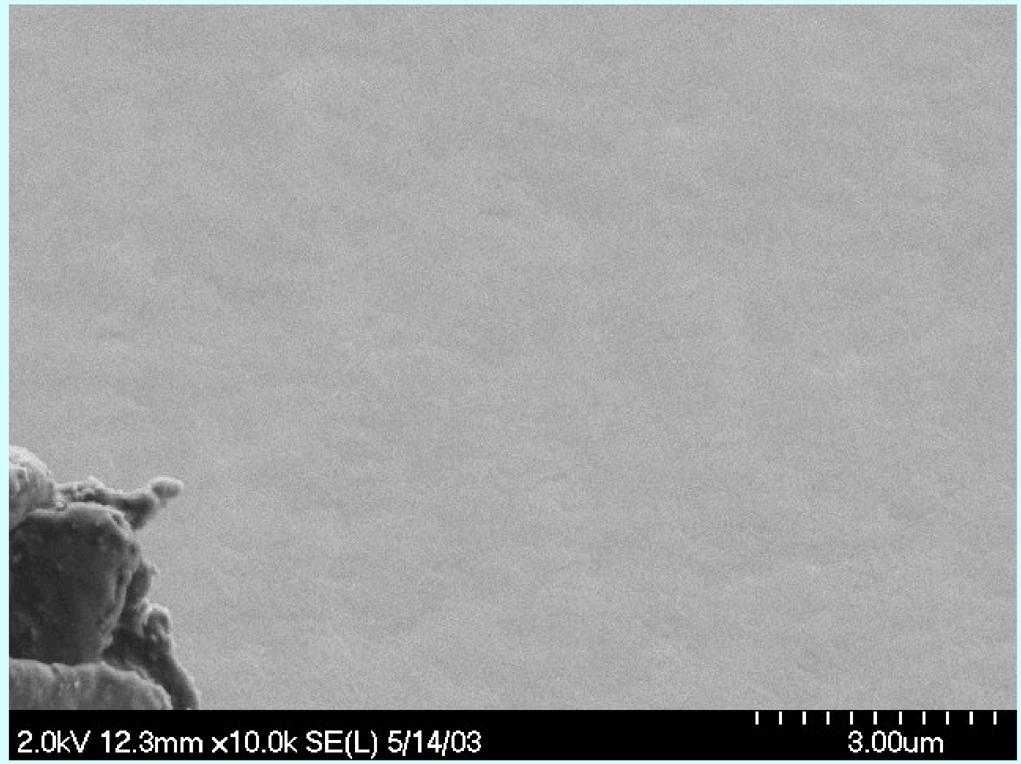






Precision Growth of GaN at Honeywell

- Highly Uniform GaN film (< 1% thickness non-uniformity across a 4” wafer)
- High resistivity GaN film (> 20 MOhm/square)
- Seed layer developed (minimized pitting)
- GaN resonator layer developed (2 micron thick layers without cracking)



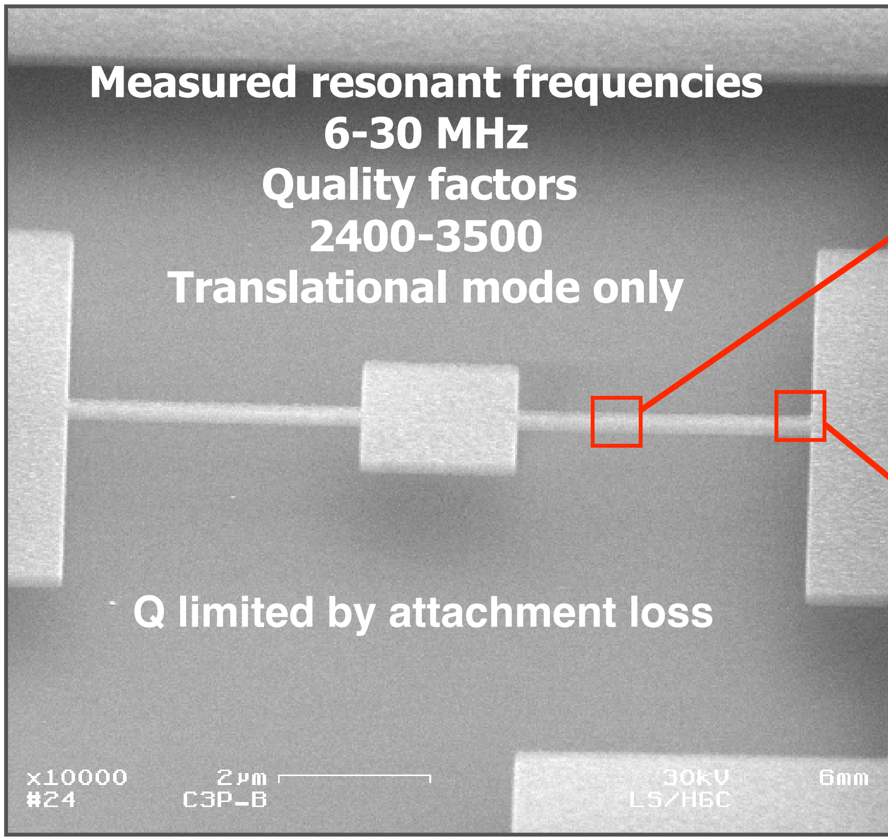
Blanket single crystal film, 1 micron thick, grown on 4 inch diameter Si wafers. Thickness and roughness controlled within few nanometers *(dust speck is necessary for focus on the mirror surface)*

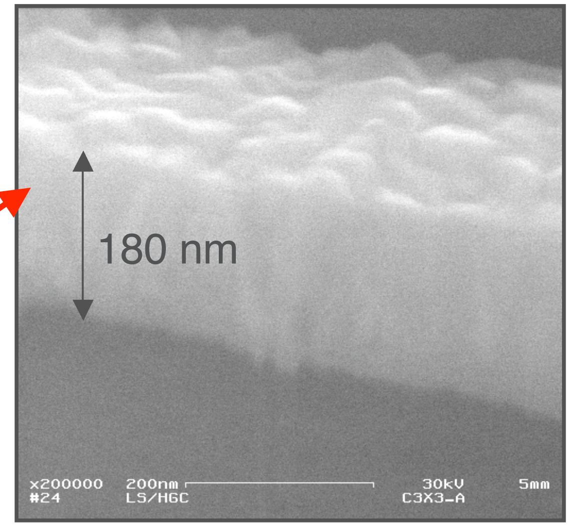
Alternate materials

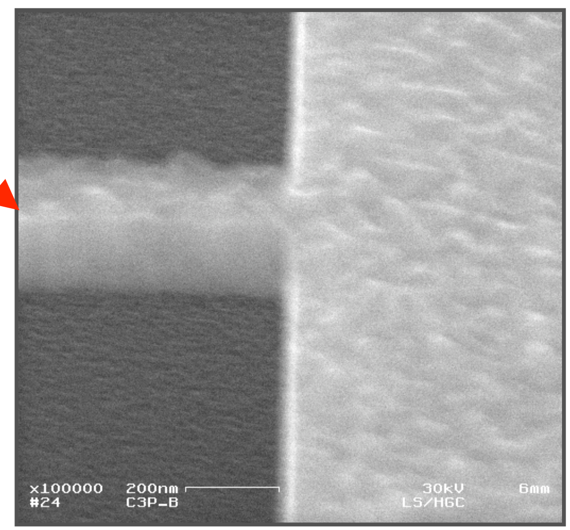
Material	Young's Mod. GPa	Density kg/m^3 10^3	Thermal Cond. W/m K 10^2	Thermal Expansion 10^{-6}/K	Specific Heat J/kg – K 10^3	Diff. K□/C□	$\square E_u \square^2 T_{\square} / C_{\square} \square$ 10^{-4}
Silicon*	166	2.3	1.57	2.3	0.668	2.35	1.55
Diamond *	1076	3.5	20.00	1.0	0.472	42.4	1.8
SiC*	700	3.2	3.50	6.4	0.8	4.4	30.6
GaAs*	75	4.9	0.46	6.9	-	-	~3
AL_2O_3	275	3.62	0.36	6.57	0.8	.45	11.1
SiO_2 (amorphous)	70	2.5	0.014	0.5	1.0	.014	.02
Quartz*	100	2.6	0.1	0.55	.787	.127	.04
Si_3N_4	255	3.1	0.19	2.8	0.7	0.27	3.8

*single crystal

CVD Diamond "MEMS Paddle"

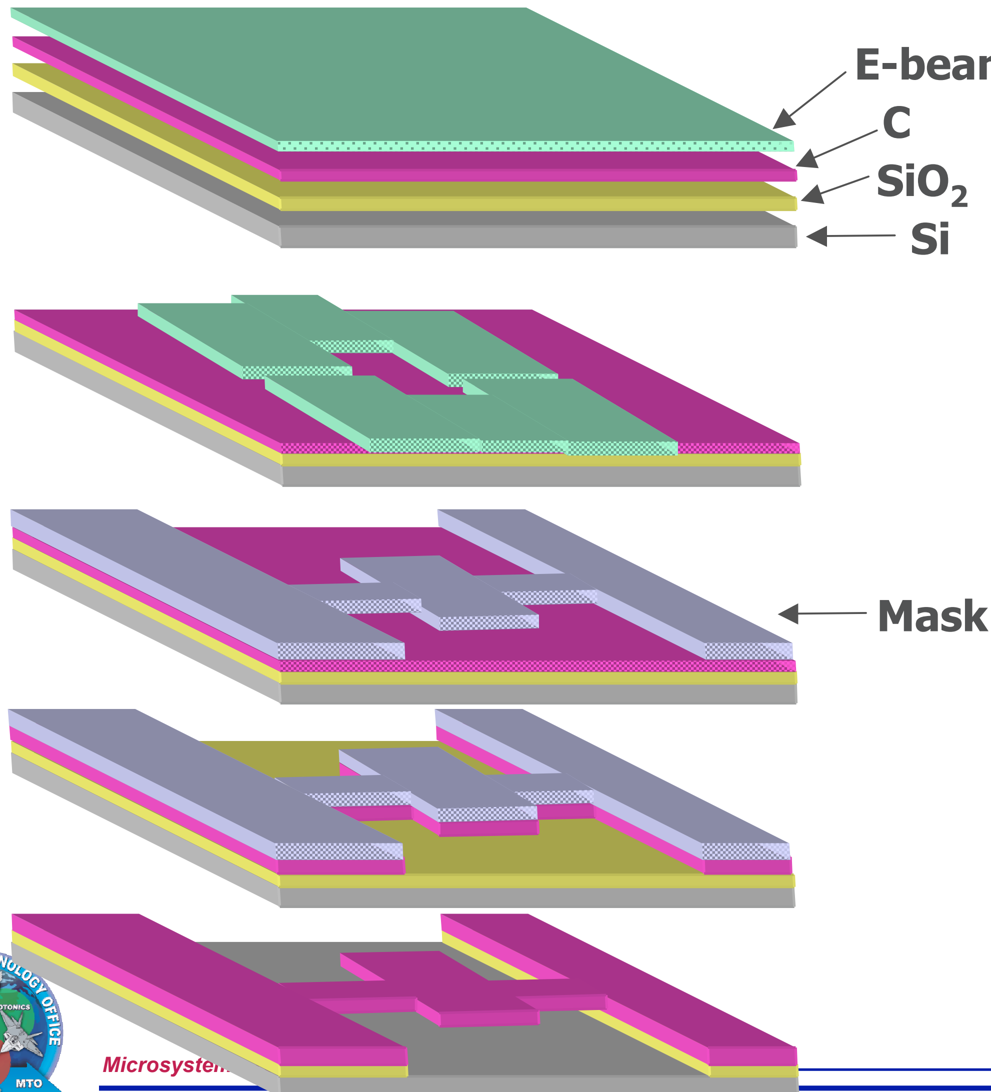






L. Sekaric – Cornell

CVD Diamond Fabrication



Start: CVD deposited material on oxide coated wafer

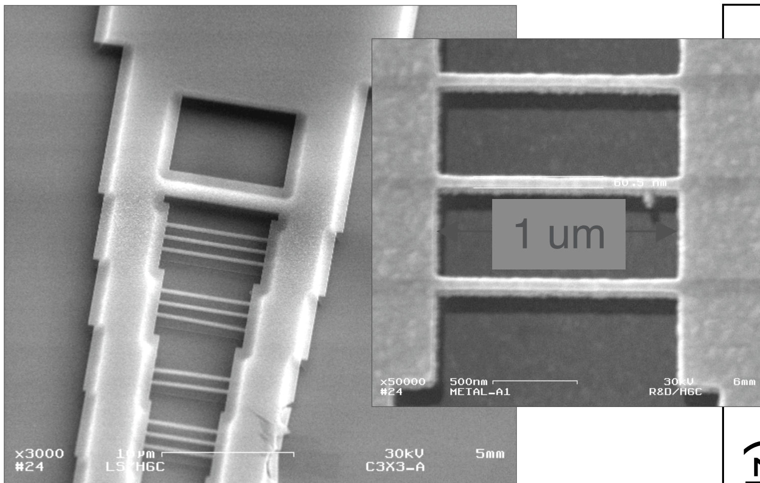
E-beam lithography and development

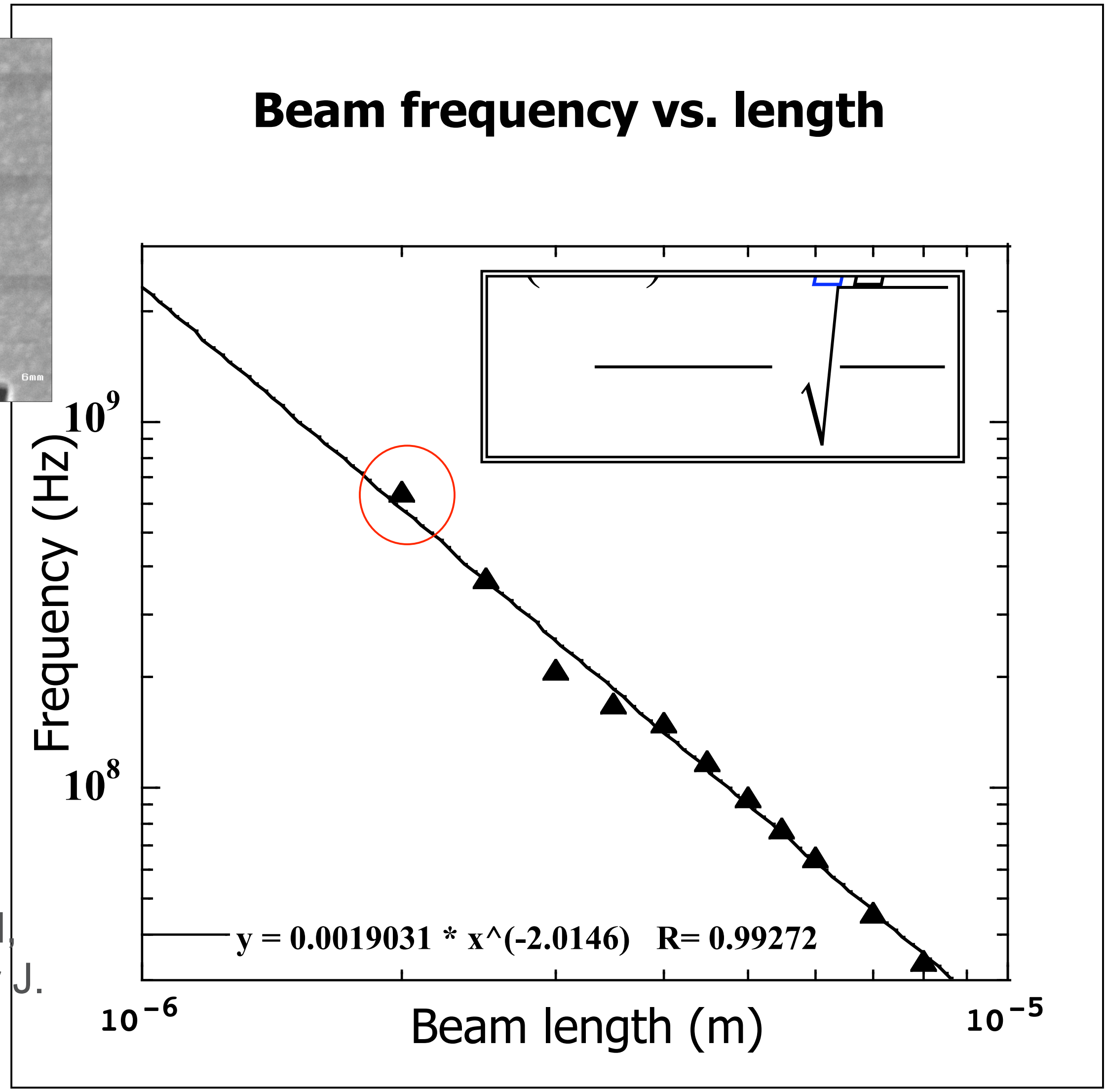
Metal mask deposition and lift-off

RIE etching

Release (in BHF)

Results: doubly clamped beams





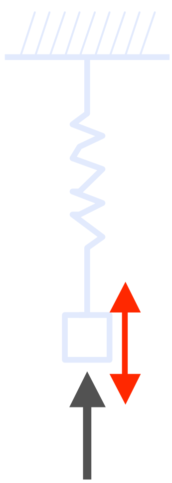
Resonant frequencies measured up to 640 MHz

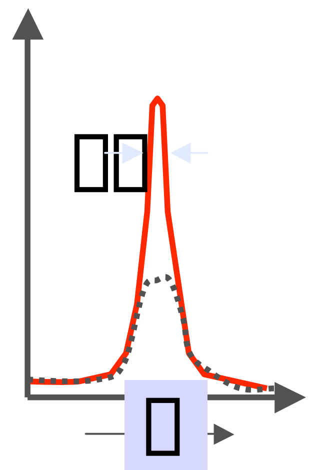
Q~1000

L. Sekaric, J. M. Parpia, H. G. Craighead, T. Feygelson, B. H. Houston, J. E. Butler J. Appl. Phys. (Dec. 2002)

Energy Dissipation in NEMS

$$\frac{1}{Q_{total}} = \frac{1}{Q_{air}} + \frac{1}{Q_{boundary}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{bulk}} + \frac{1}{Q_{Surface}}$$





$$\Delta x_{noise} \approx \left(\frac{kT\tau}{M\omega Q}\right)^{1/2}$$

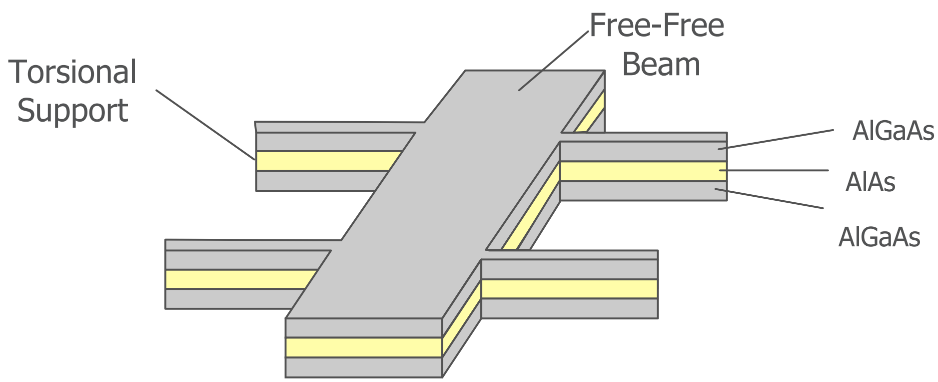
Fluctuation Dissipation Theorem

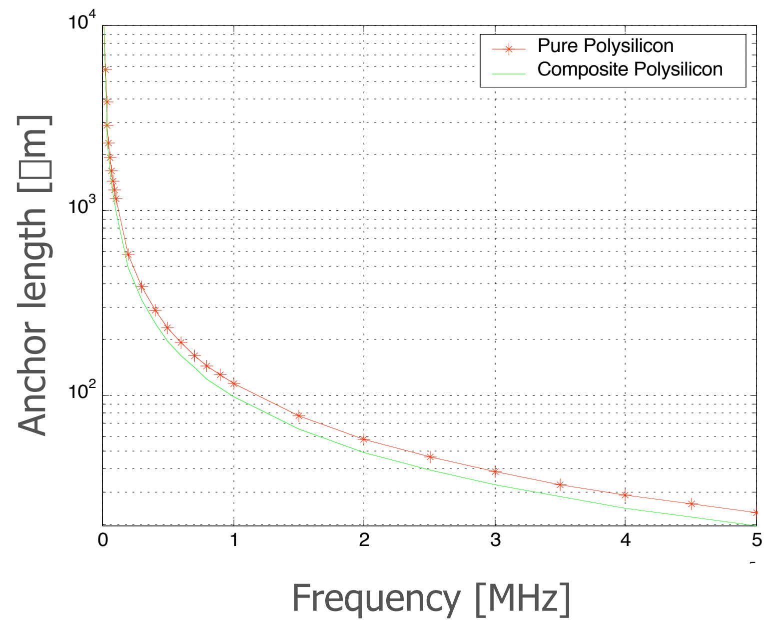
Contributing processes:

- metal films
- viscous friction
- acoustic radiation
- boundary losses
- processing induced damage
- thermoelastic dissipation
- surface effects (not just roughness)
- other?

What are the *fundamental* limits?

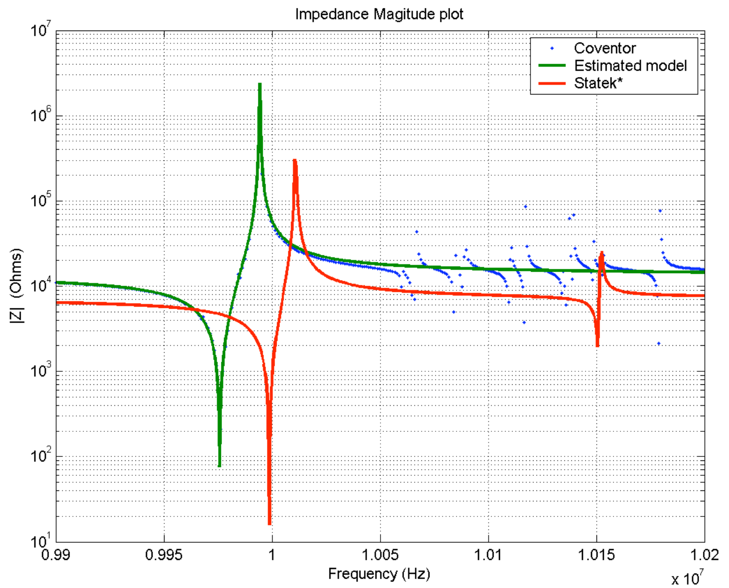
Modeling and Design: free-free resonators

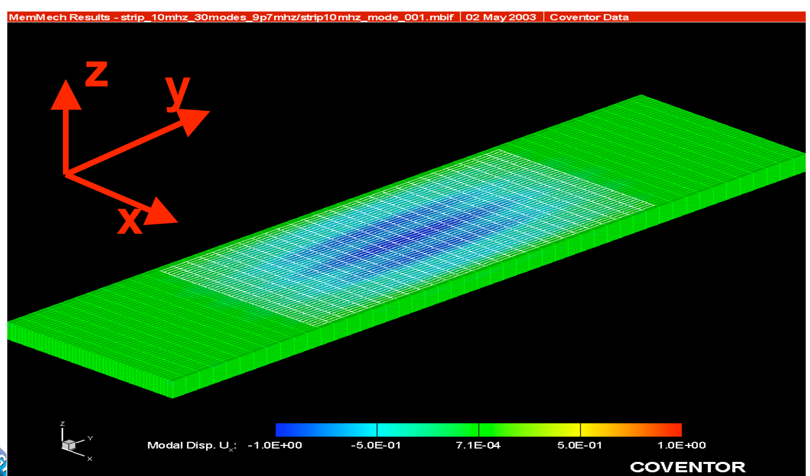




- **Initial model validation complete**
- **Devices for full model validation currently in fab**
- **Low-frequency (up to 250MHz) filter fab run scheduled for mid-August**

Benchmarking New 3-D Software with Experimental Quartz Resonator Data





Details:

- 10 MHz TS mode AT-cut quartz strip resonator by Statek
- Analysis tool: beta version of commercial FEA software (Coventor)
- Compare FEA to measurements made by Statek
- Benefits: Demonstration of a high degree of correlation provides confidence in the new tool

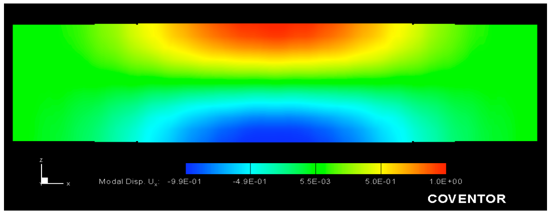
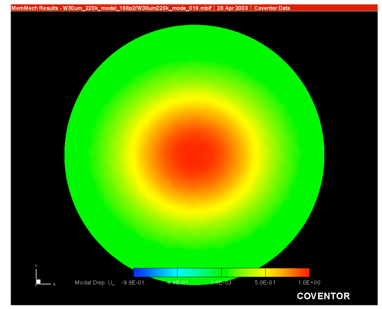
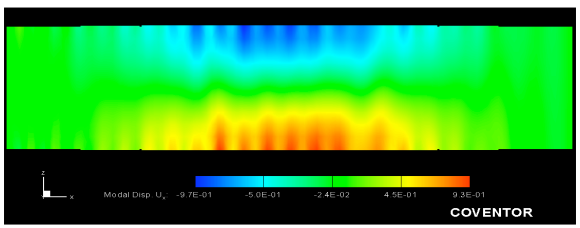
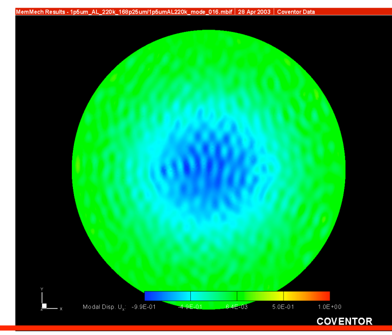
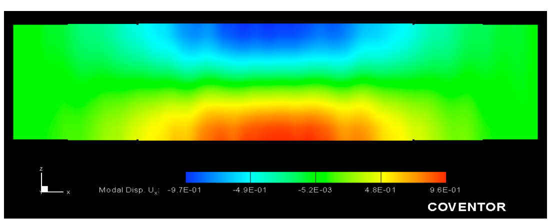
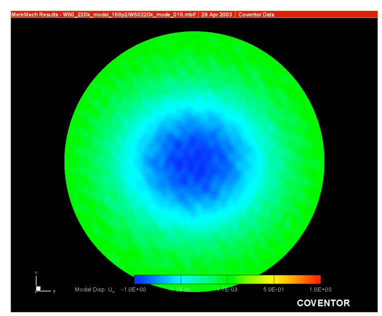
Equivalent circuit elements:

•Experimental data:
C_0=2.24pF, C_1=5.45fF, R_1=15.5Ω

•Numerical analysis:
C_0=1.17pF, C_1=4.36fF, R_1=75.5Ω

***Statek measurements provided by Greg Burnett**

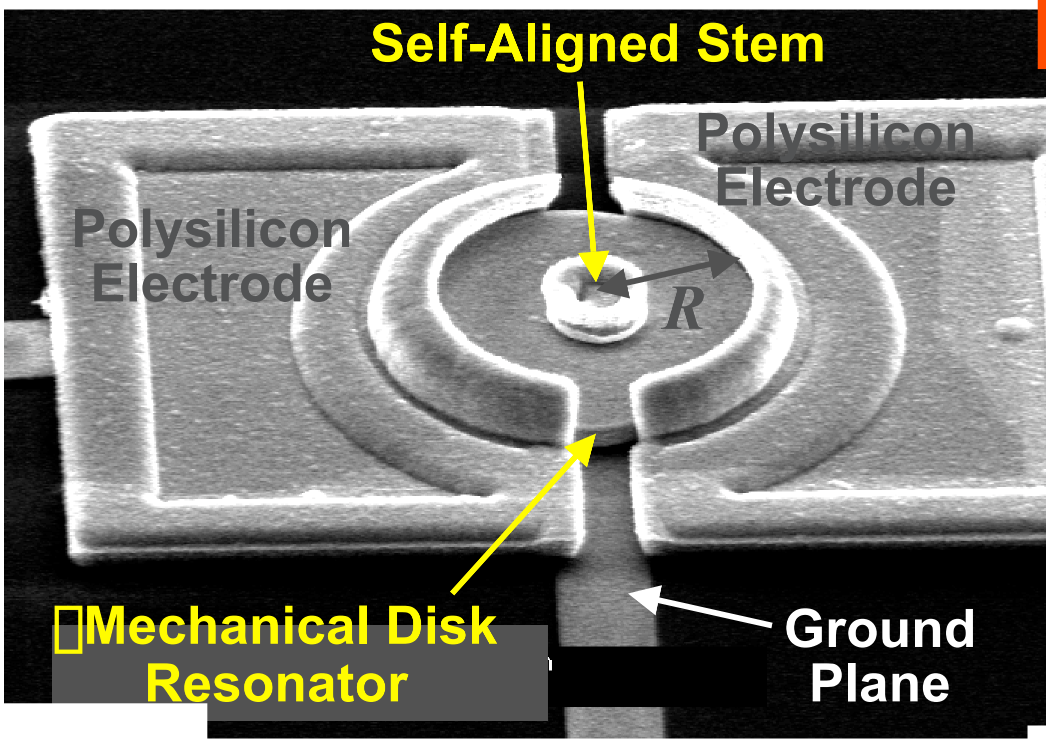
Energy Trapping vs. Electrode Width - Optimizing Q

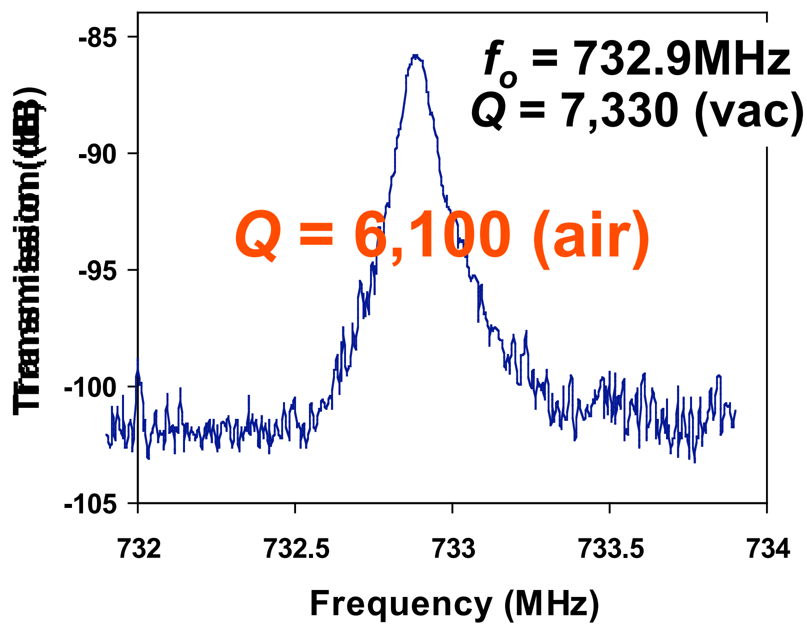
Electrode width	Cross-section view (X-Z)	Top view (X-Y)	Remarks
30μm			• Best trapping under resonator area • little flexural component
40μm			• large flexural component
50μm			• trapping not confined to resonator but extends under electrodes

733 MHz Self-Aligned Radial Contour-Mode Disk μMechanical Resonator

- Self-aligned stem for reduced anchor dissipation
- Polysilicon electrodes for better gap stability
- *Q* > 6,000 seen even in air (i.e., atmospheric pressure)!
- *Below*: 20 μm diameter disk

Design/Performance:
R=10μm, *t*=2.1μm, *d*=800Å, V_P=6.2V
f_o=732.9MHz (2nd mode), *Q*=7,330



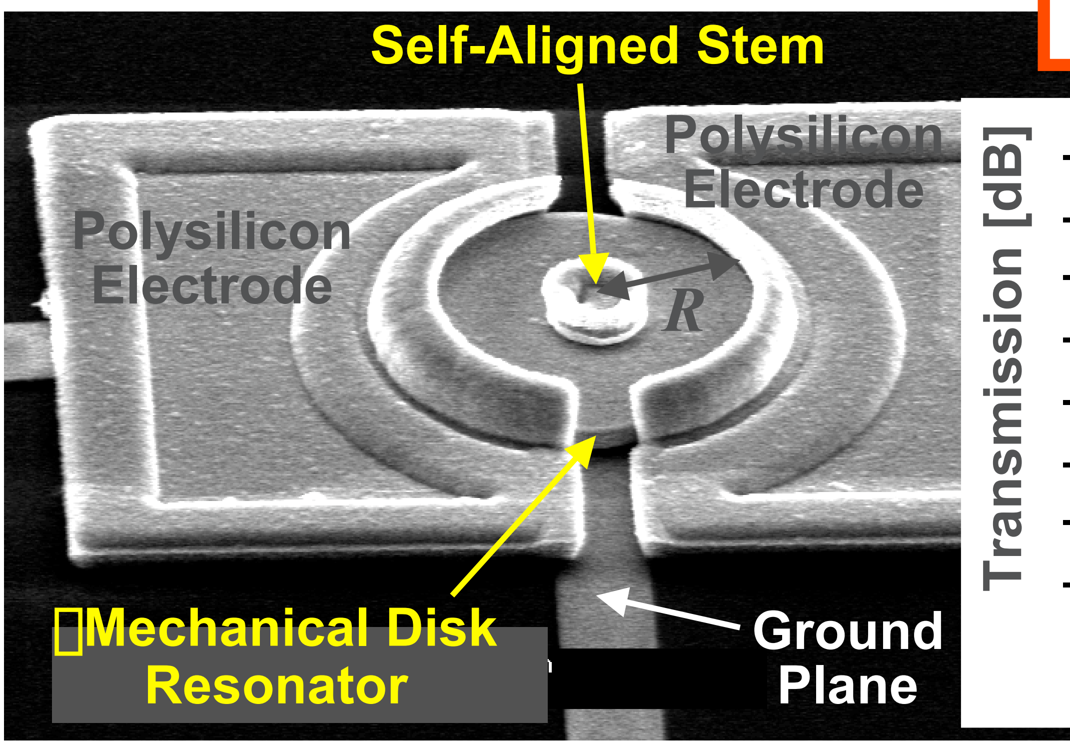


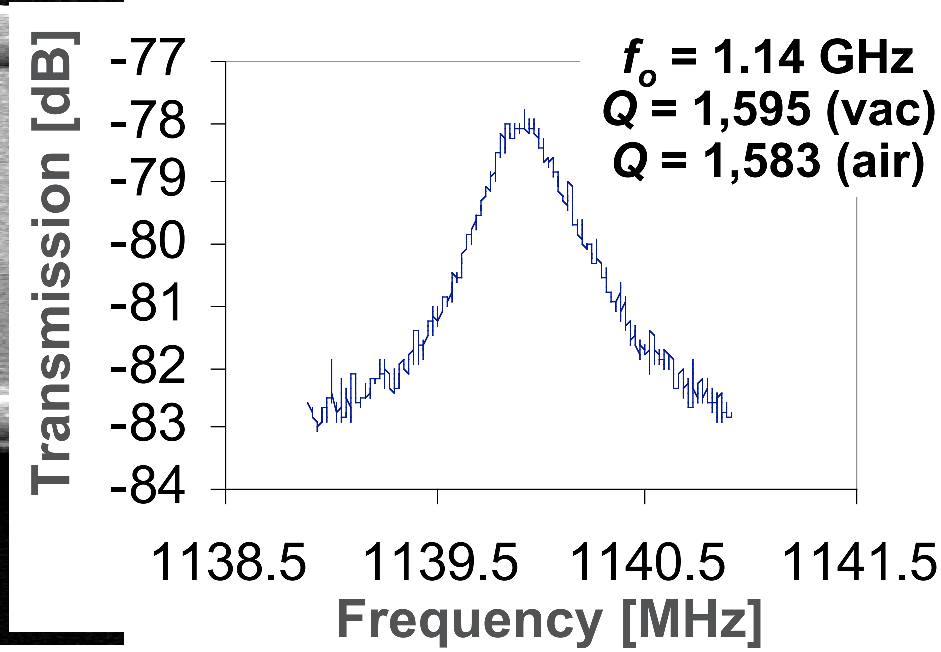
[U. Michigan, 2002]

1.14-GHz Self-Aligned Radial Contour-Mode Disk □Mechanical Resonator

- Self-aligned stem for reduced anchor dissipation
- Operated in the 3rd radial-contour mode
- *Q* > 1,500 seen even in air (i.e., atmospheric pressure)!
- *Below*: 20 □m diameter disk

Design/Performance:
R=10□m, t=2.1□m, d=800Å, V_P=6.2V
f_o=1.14 GHz (3rd mode), Q=1,595

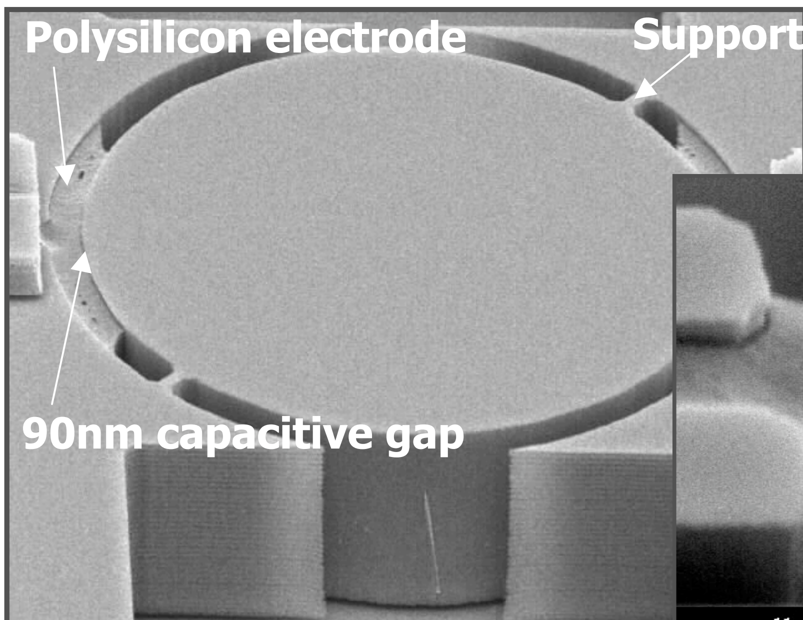


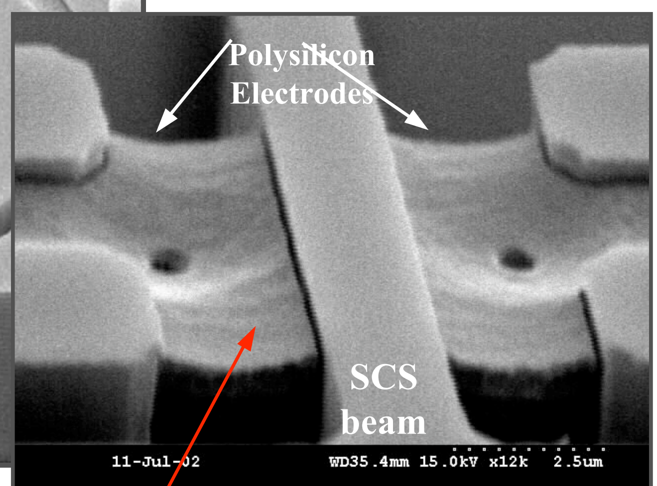


[U. Mich., 2003]

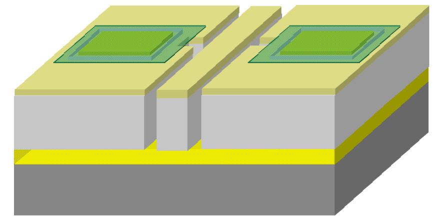
VHF and UHF Resonators

- SOI-Based HARPSS Technology
  - 10-30 micron thick films
  - Ultra-stiff resonators with high width to height ratio
  - Results in smaller equivalent resistance → larger SNR

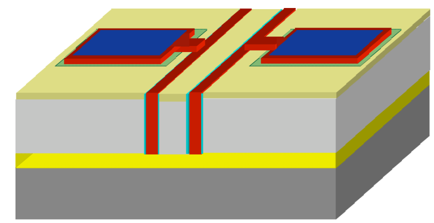




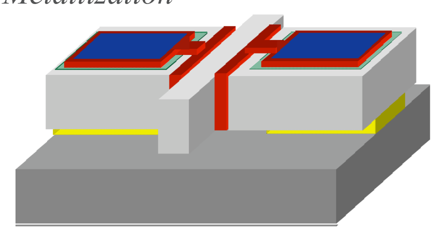
gap spacing → *goal: 10nm*



Pad oxide and LPCVD nitride for insulation. Trenches define resonator boundary.

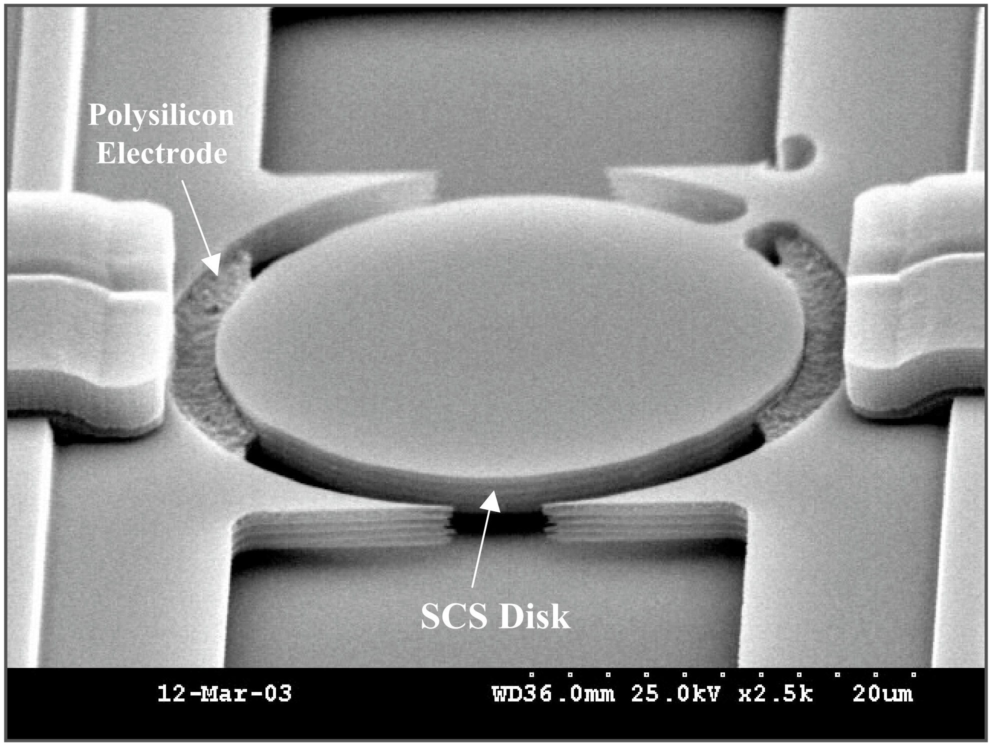


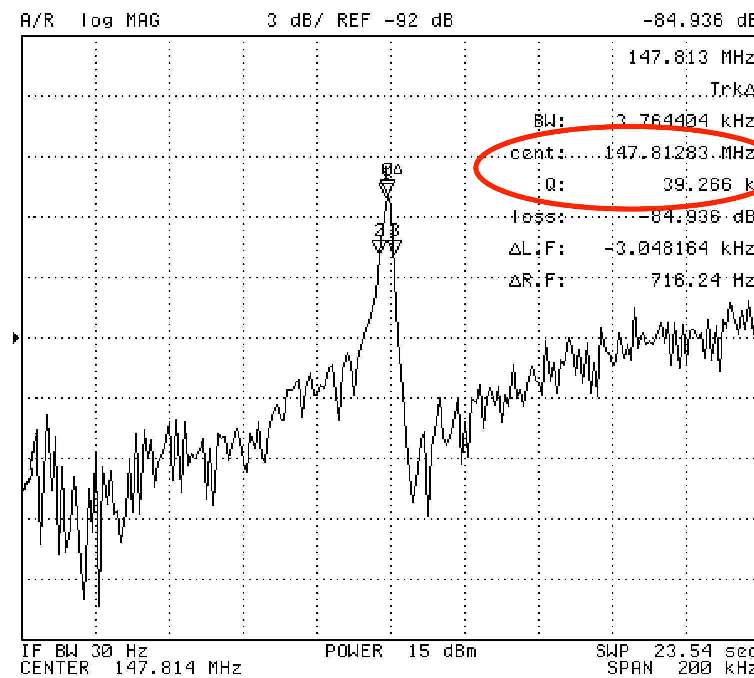
LPCVD sacrificial oxide and polysilicon. Polysilicon patterned, Metallization



Electrode polysilicon patterned release openings etched in SCS. Release and undercut in HF:H_2O

Single Crystal Silicon Disk Resonators





side-supported SCS disk resonator

90nm capacitive gaps

Diameter=30□m, Thickness =3 □m

Q=40,000 @ 147.8MHz

TCF of Capacitive HARPSS Resonators

❑ Temperature Coefficient of Frequency

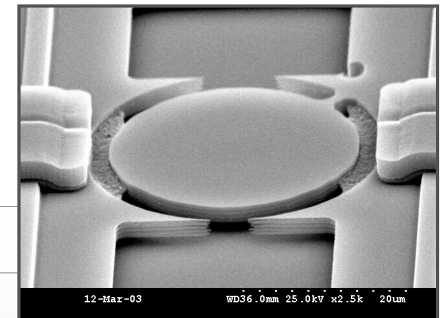
- Temperature dependency of the resonating material's Young's modulus will be the dominant contributing factor.
- Thermal Expansion → Dimensional Change

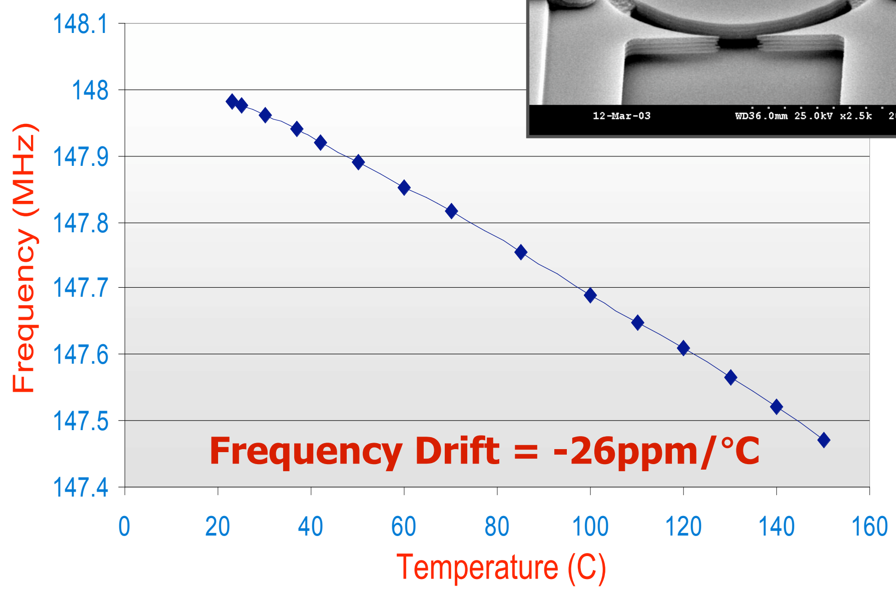
Mechanical Stiffness

Electrical Stiffness

$$\frac{1}{f}\cdot\frac{\partial f}{\partial T}=\frac{1}{2}\cdot\frac{1}{E}\cdot\frac{dE}{dT}-\frac{1}{R}\cdot\frac{dR}{dT}-\frac{3V_p^{\,2}A_e\varepsilon}{Kg^3}\cdot\frac{1}{g}\cdot\frac{dg}{dT}$$

Dominant term

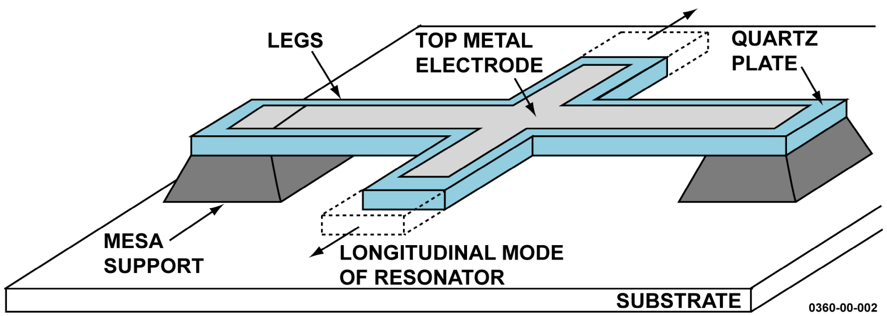




Measured temperature characteristic for the 150MHz disk resonator

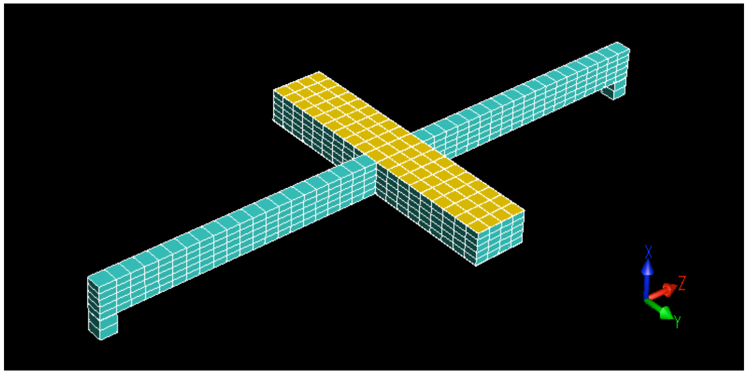
Alternate Designs for Large Arrays

- Using the same fabrication process, designs which rely only on lateral dimensional changes can be fabricated in temperature compensated X-cut quartz



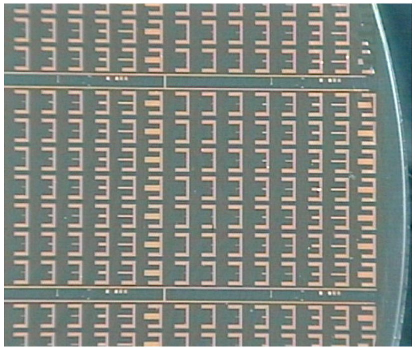
For 300 MHz: resonator length L ~ 10 □m

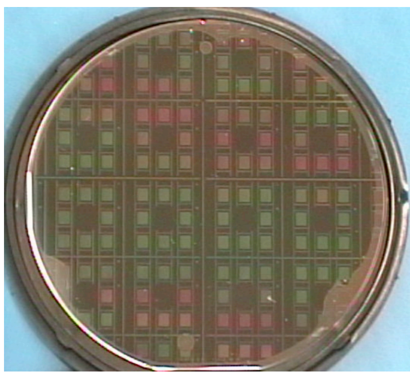
(resonant frequency scales like 1/L)

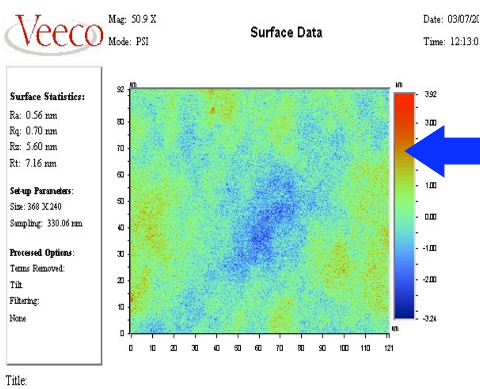


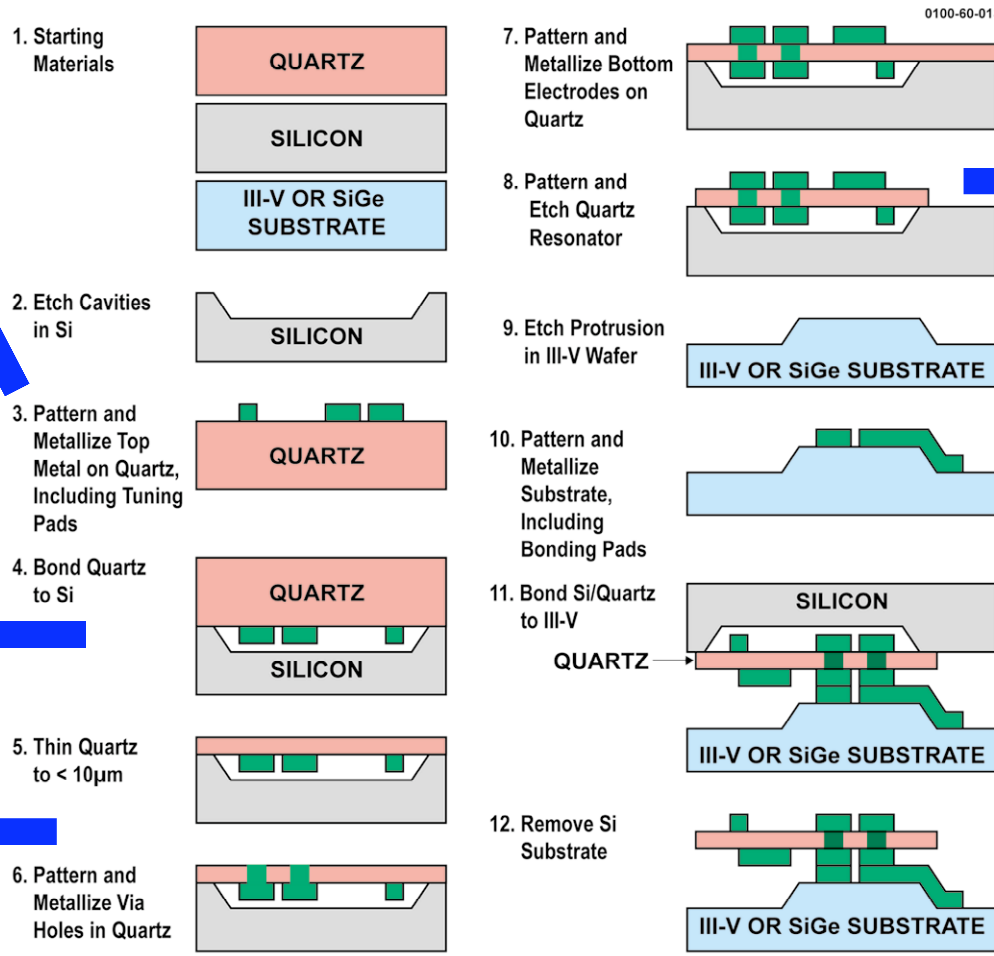
Meshed longitudinal design in 3-D Simulator

Integrated Thin Film Quartz Resonators

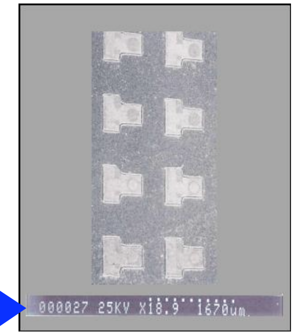


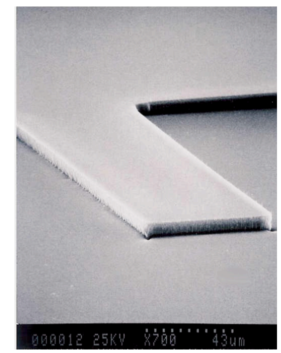


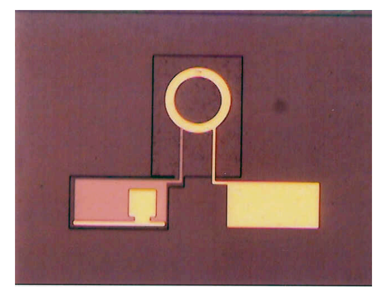




Process Flow for Nanoresonators

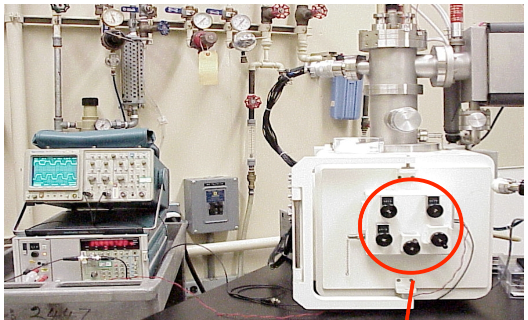




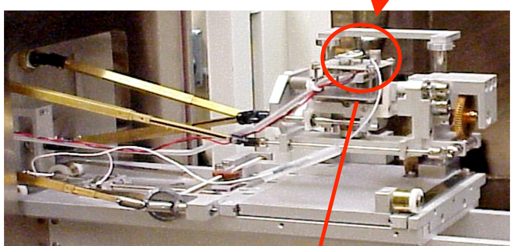


HRL Labs

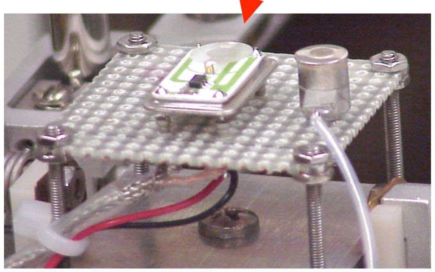
FIB Frequency Tuning During Real-Time Monitoring



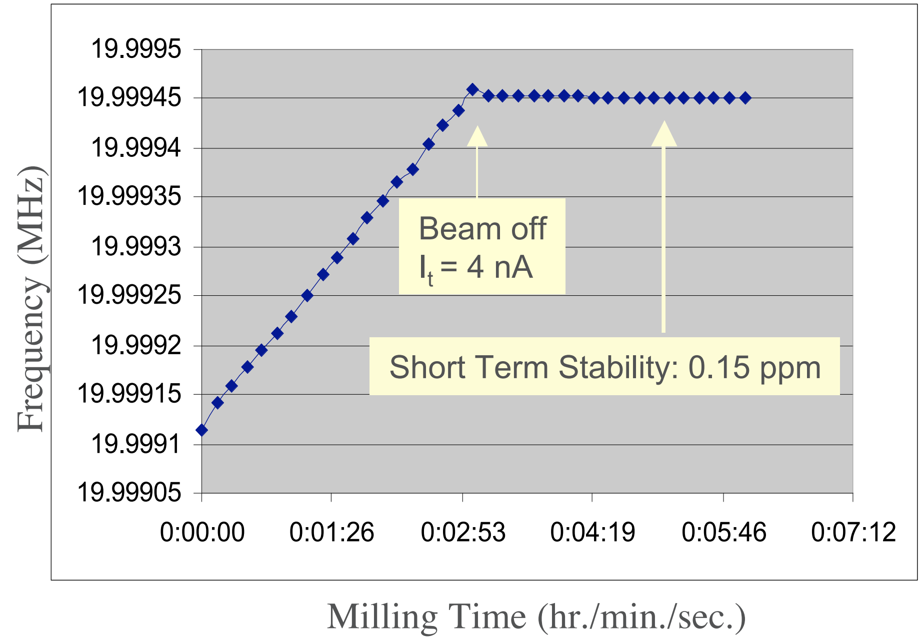
FIB System

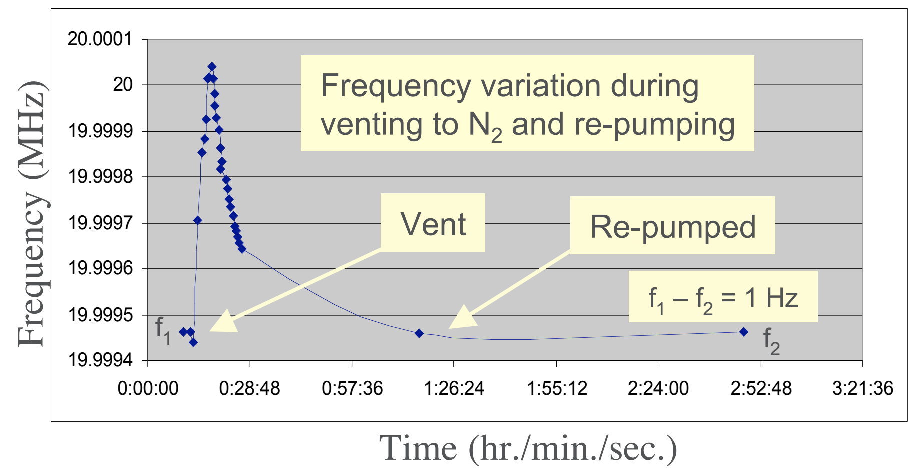


FIB Chamber



Commercial 20-MHz Shear-Mode Oscillator



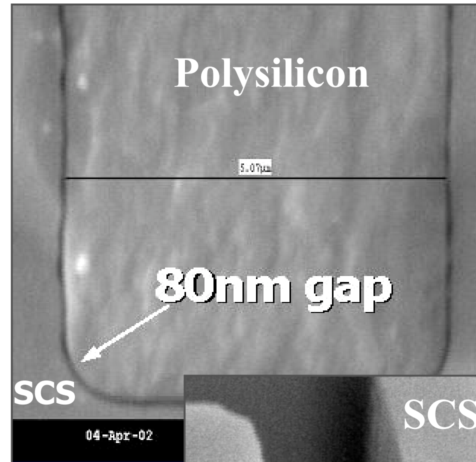


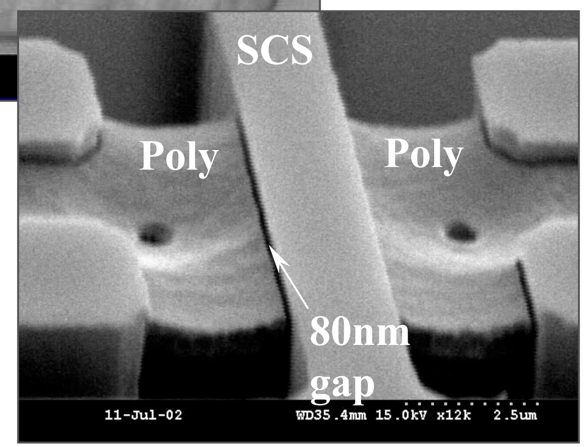
Nanometer Capacitive Gaps

- Self-aligned vertical capacitive gaps defined by the sacrificial oxide layer

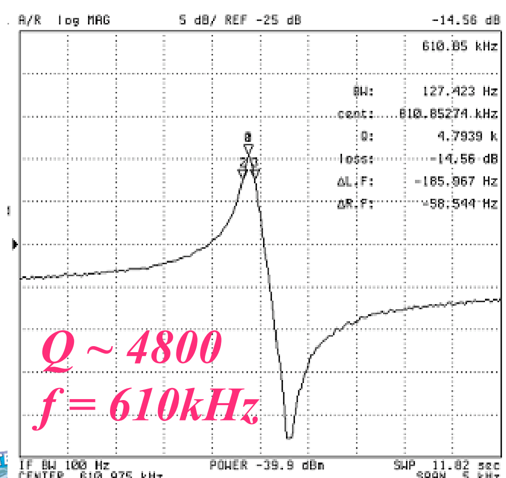
  → *Potentially reducible to 10nm*

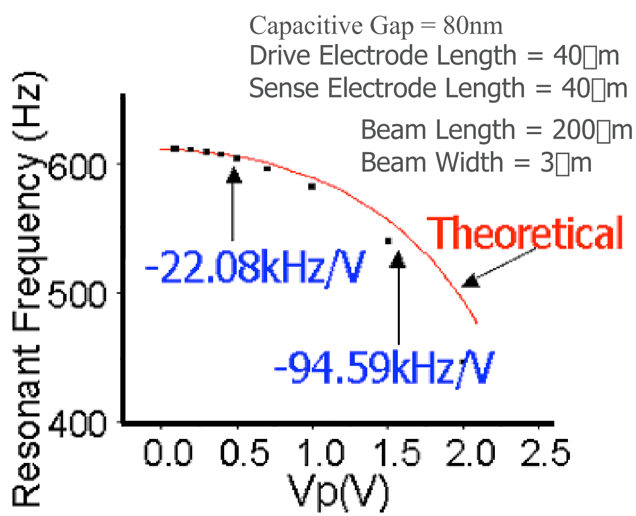
$$R_r \propto gap^4$$





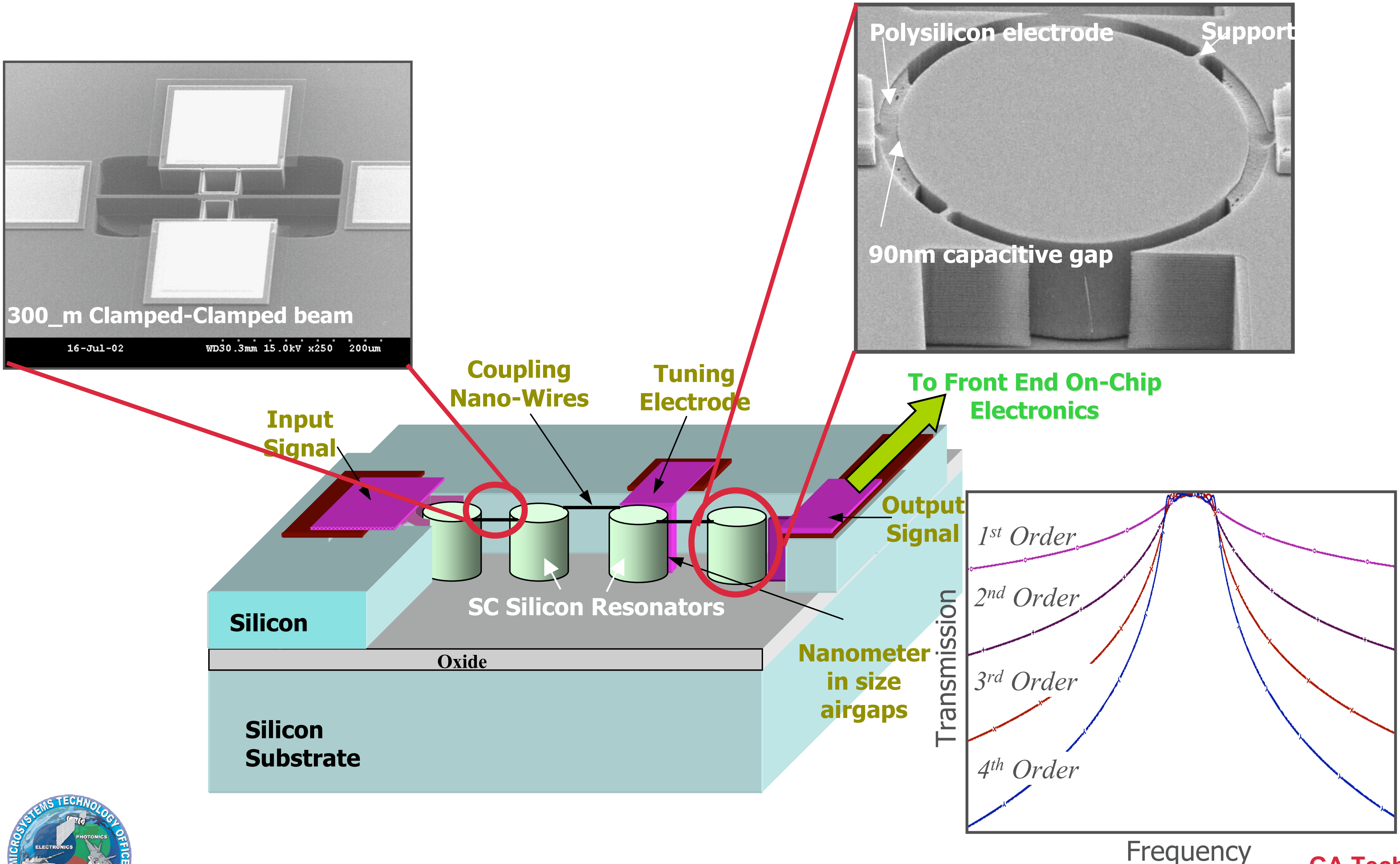
- Capacitive gaps as small as **80nm** demonstrated





- 28% tuning range for the 80nm gap device

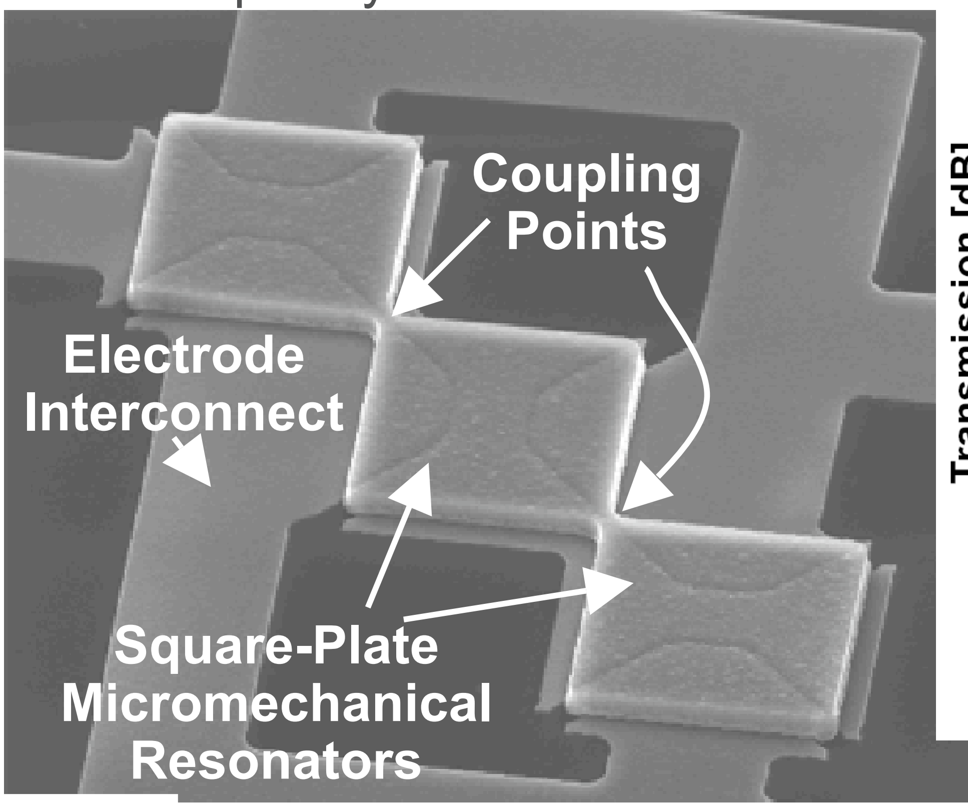
SOI Nano-scale Disk Resonator Arrays

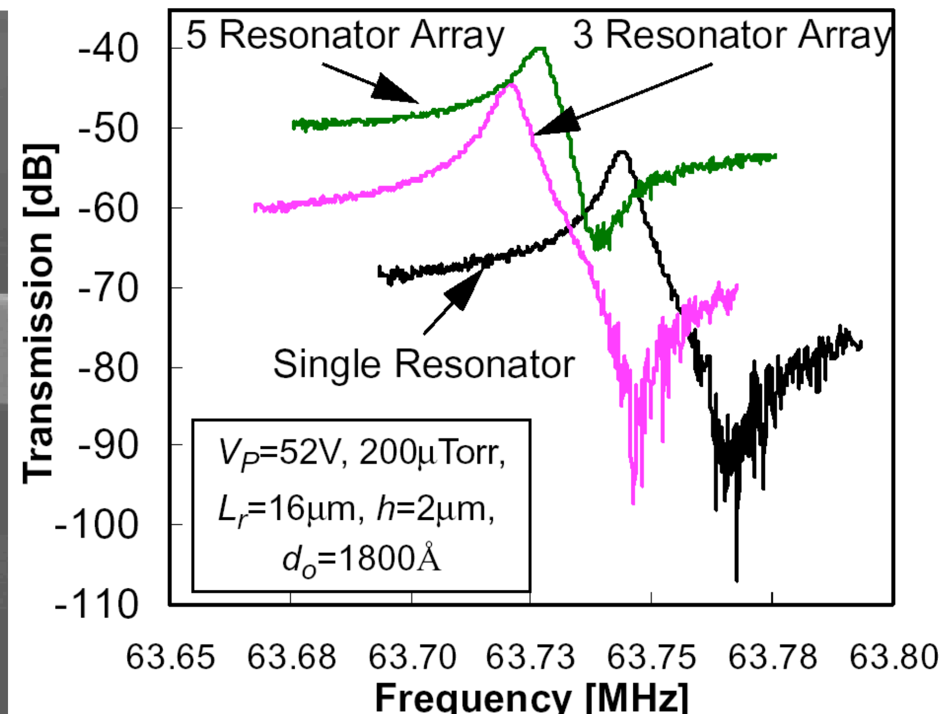


GA Tech

Mechanically-Coupled Resonator Arrays for Higher Power Handling

- *Problem*: small size ⇨ lower power handling
- *Solution*: combine signals from an array of microresonators
  - *problem*: all resonators must be at the same frequency
  - *solution*: mechanically couple them to force all to resonate at the same frequency

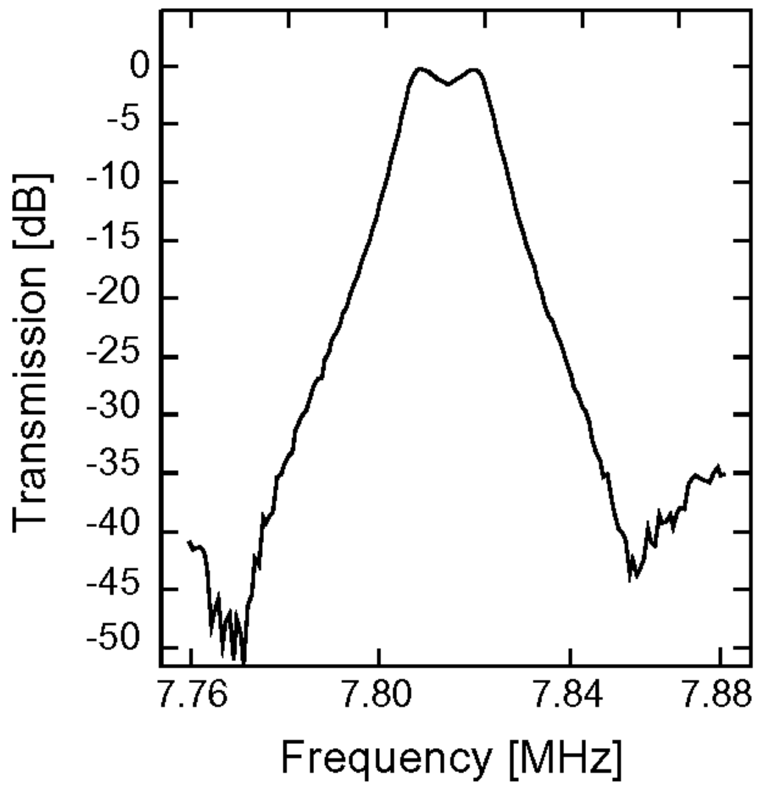


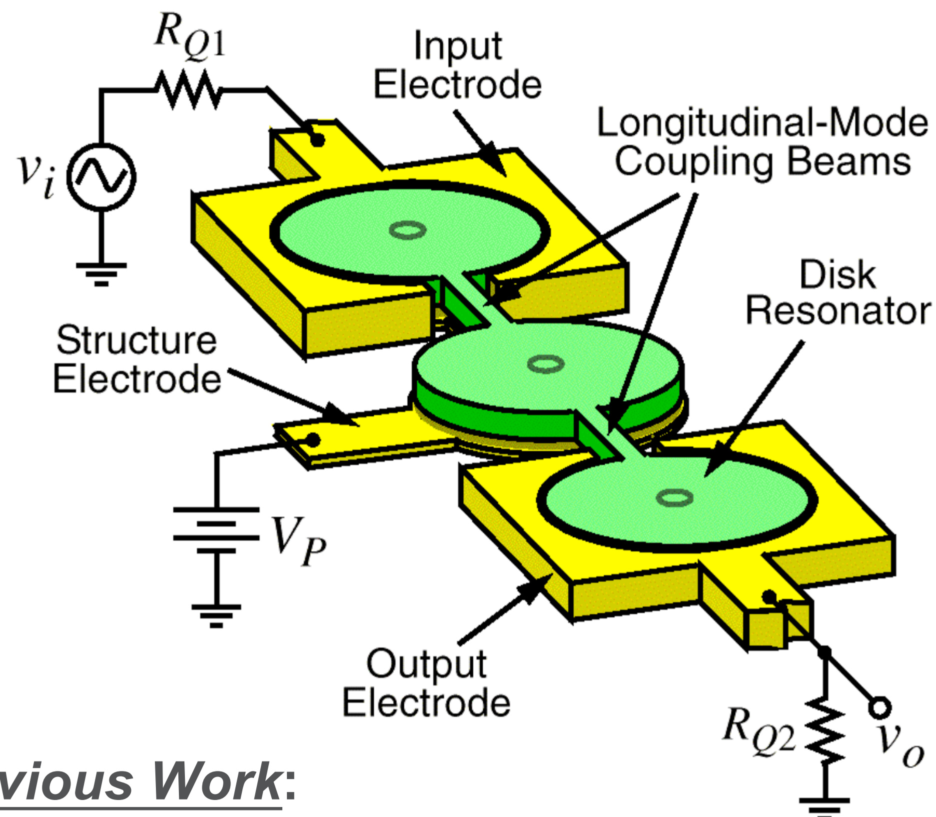


[Demirci, Nguyen 2003]

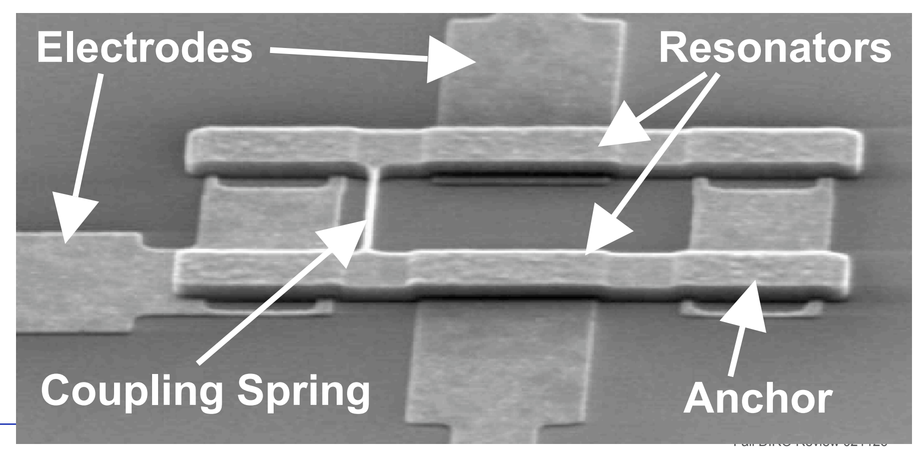
Future Work: □Mechanical Filters

- Lower the impedance of GHz micromechanical resonators
- Create □mechanical circuits using such resonators
- *Example*: □mechanical filter



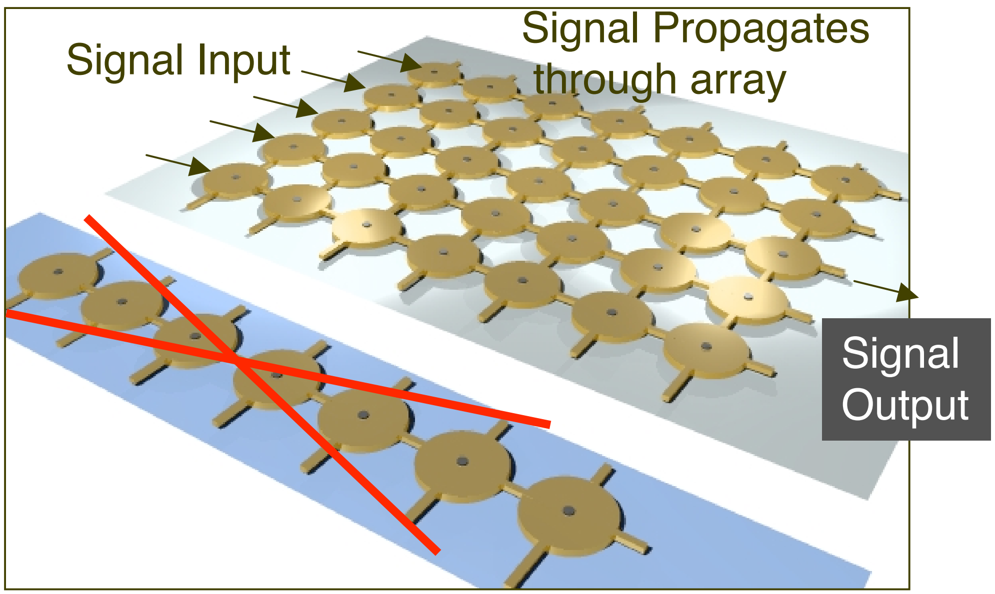


Previous Work:

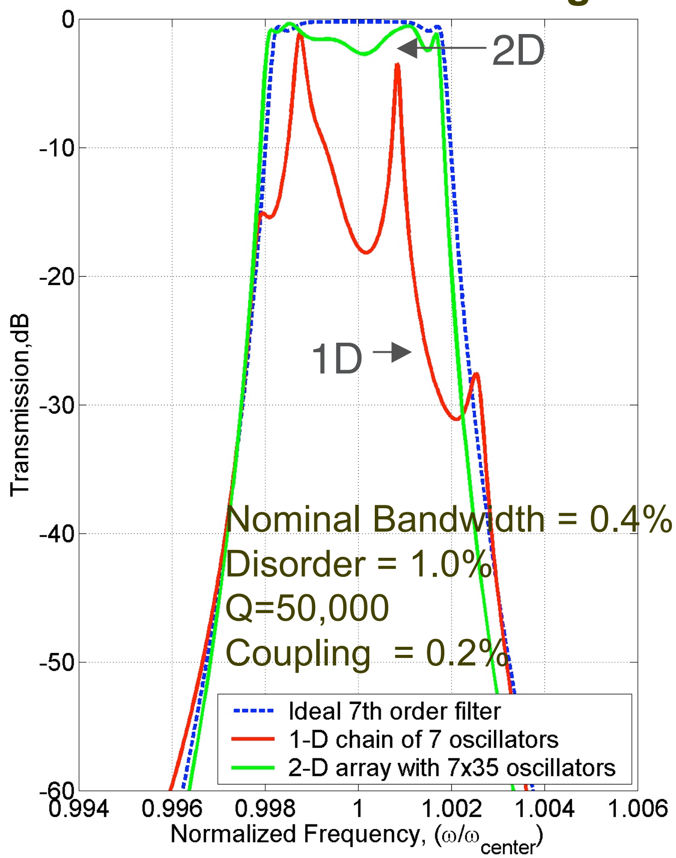


Can Trimming be Avoided

- We have invented a 2-D array approach that allows disorder to be averaged in a second dimension resulting in significantly improved performance.
- Can "trimming" be avoided?

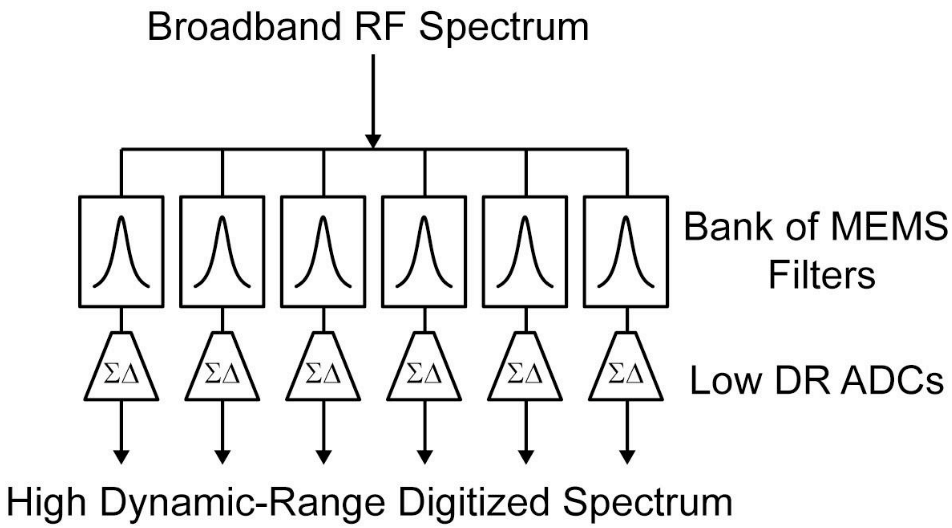


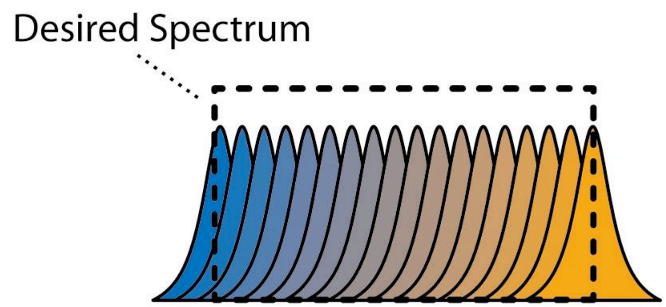
RF/Baseband Filter Design



J. Judge, et al. in press

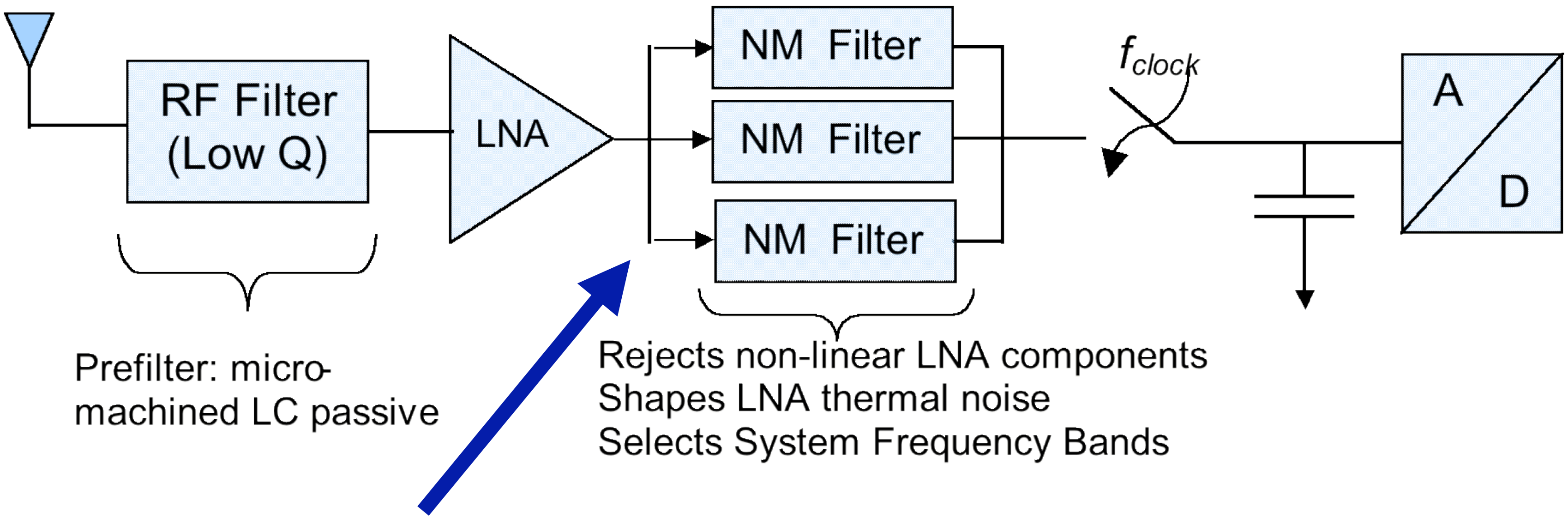
MEMS RF Spectrum Analysis





- Broadband RF "digital" radio requires fast high, dynamic range ADC and broadband RF front-end
- Bank of active MEMS resonators selects narrowband signal
- Low performance __ converters digitize each narrowband spectrum
- Relaxed requirements on ADC performance result in power savings and integration

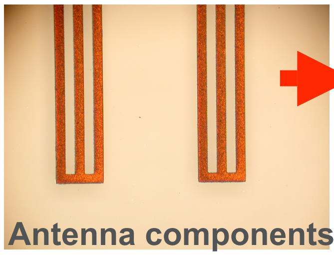
“Analog OFDM” Subsamping Transceiver Using NM Filters

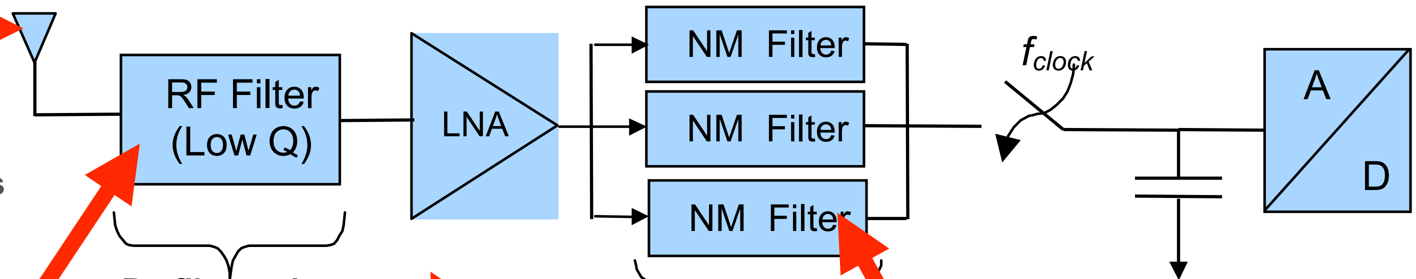


NM filters enable an integrated “comb”

Note: no local oscillator → reduced power

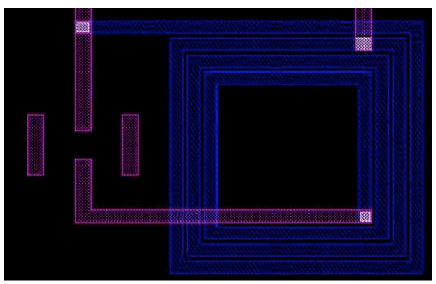
Future Directions



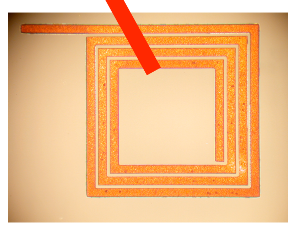


Prefilter: micro-machined LC passive

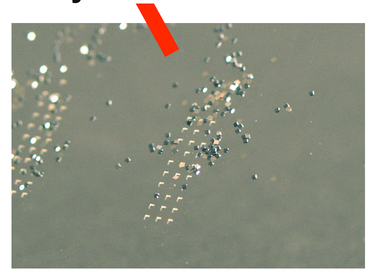
Rejects non-linear LNA components
Shapes LNA thermal noise
Selects System Frequency Bands



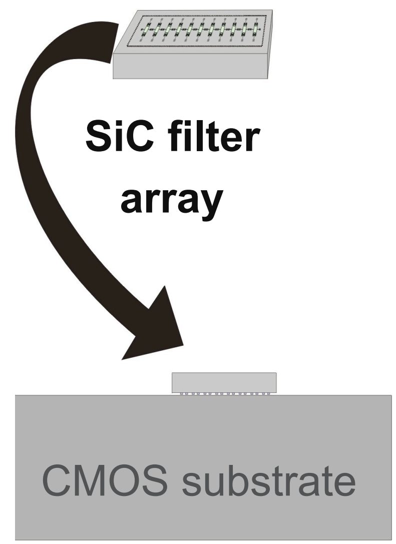
Autotransformer for Broadband match



Spirals on dielectric substrate

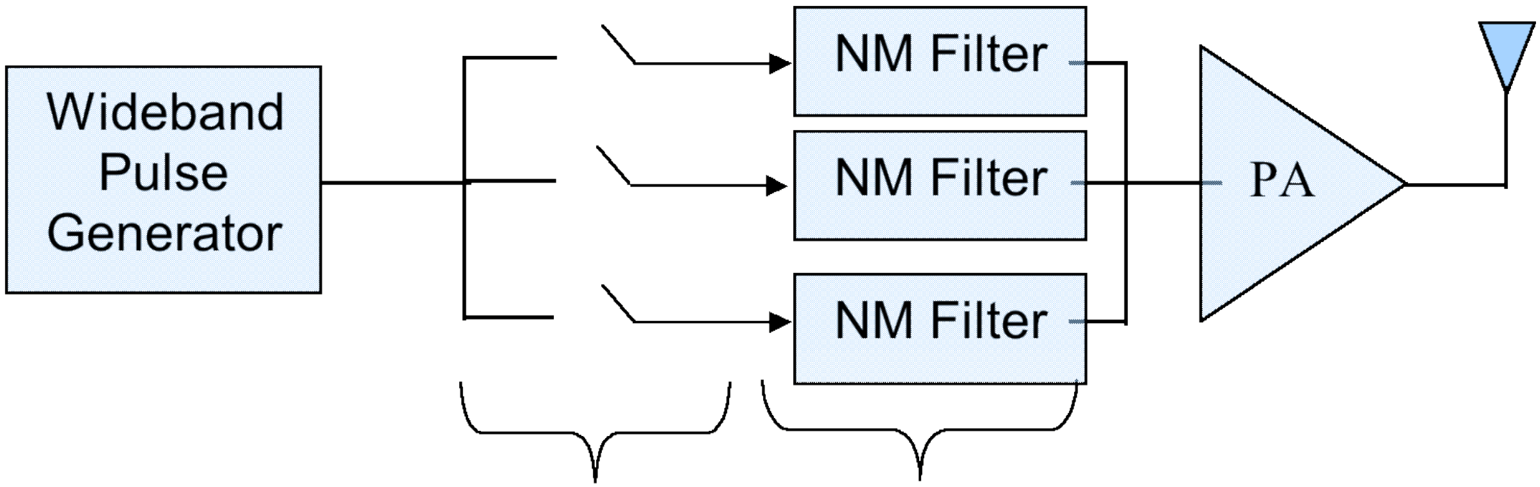


Assembly of NM filters



High performance antennas, autotransformers, and inductors

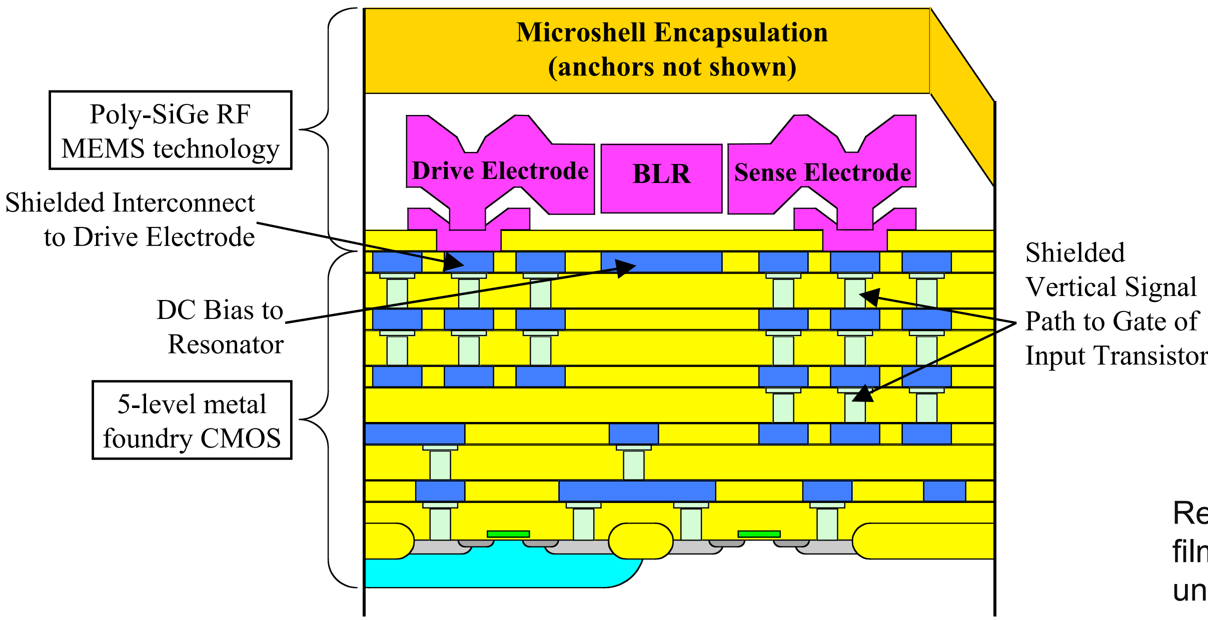
Transmitter Architecture

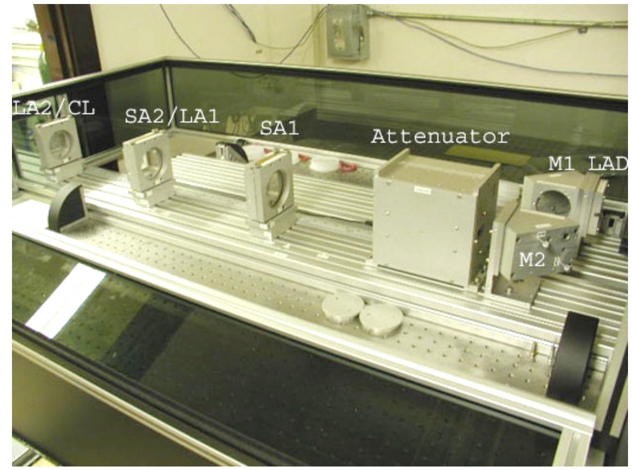


- Switches select transmission tones

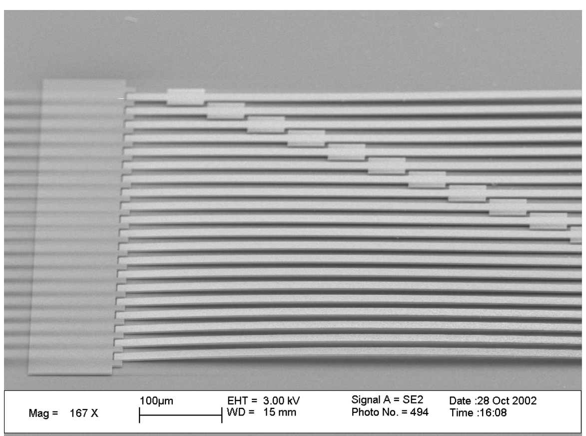
- Shapes wideband pulse into tones amplified & transmitted by PA

Post-CMOS Poly-SiGe MEMS

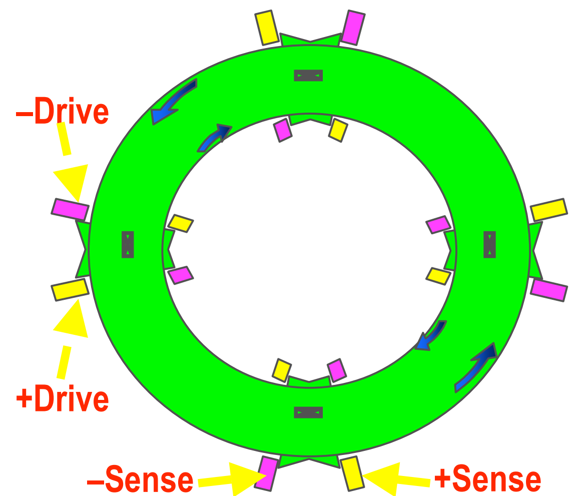




Results (IEDM-02 and MRS Fall-02): 500 nm film can be re-crystallized without affecting underlying Al metallization



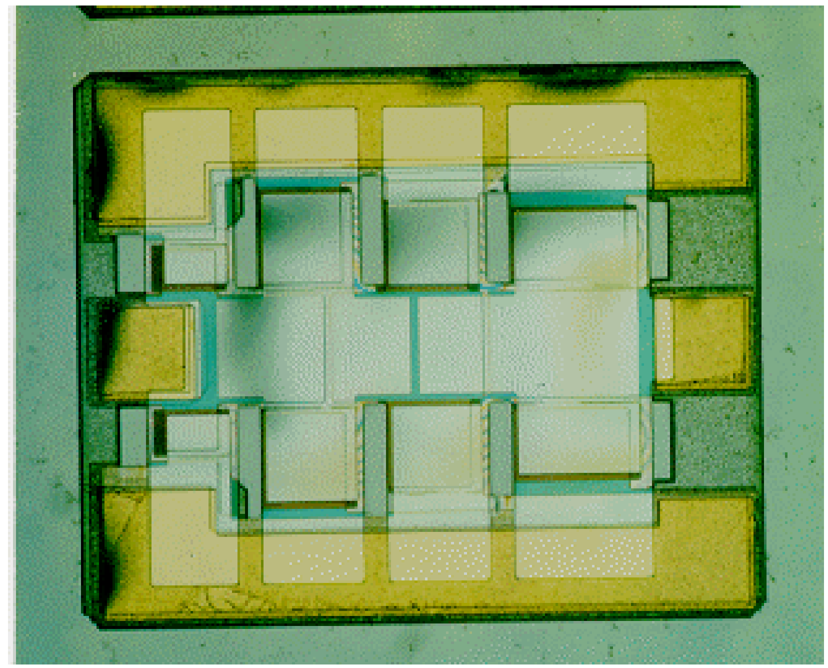
Bi-layer deposition process (2.8μm) to balance strain and strain gradient
Residual stress: 3 MPa tensile



Thin-Film Bulk Acoustic Resonators

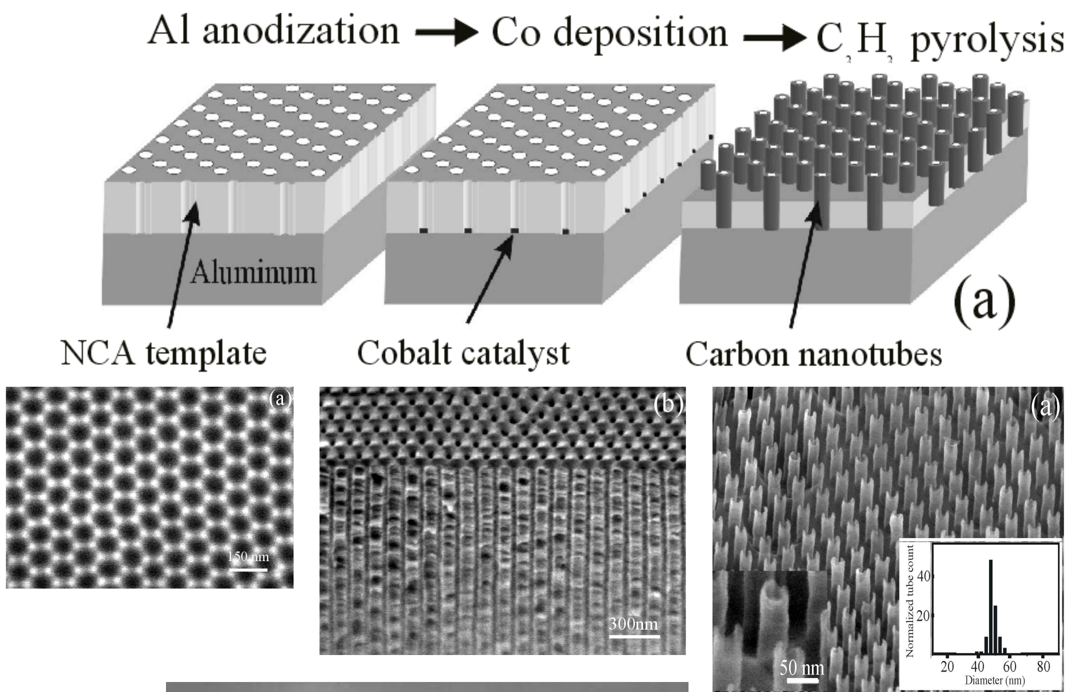
- Commercial off-the-shelf discrete components
- Frequency is a function of thickness → single frequency per FBAR chip

- Use to demonstrate new transceiver architectures

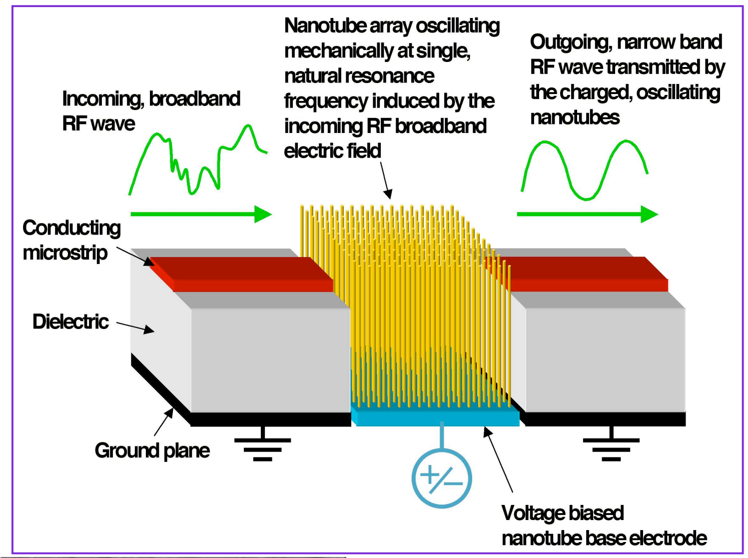


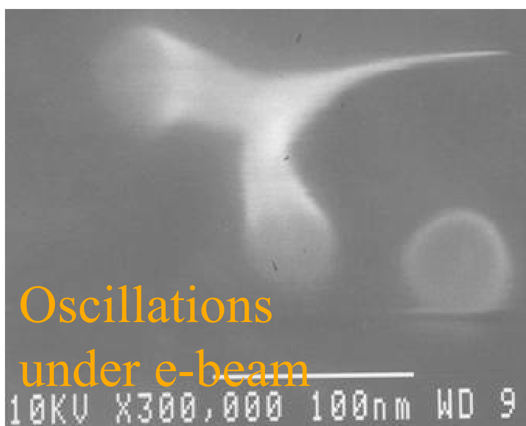
Agilent Technologies FBAR duplex filter

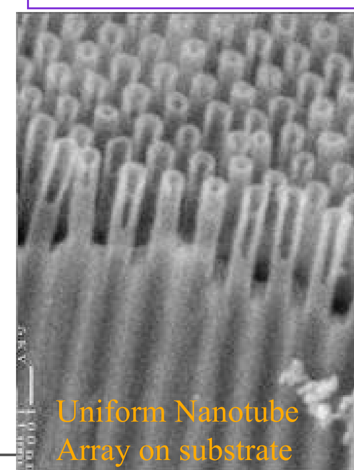
Carbon Nanotube Filter



Nanotube Array RF Filter



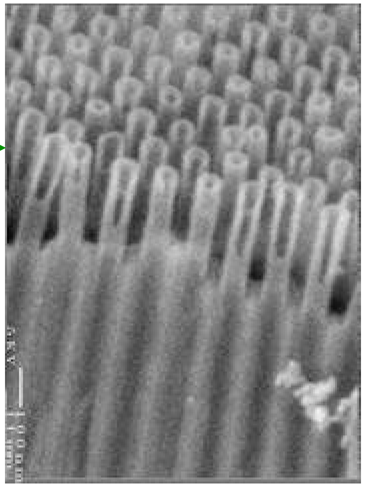




Creating and assembling a uniform array of MWCNT's for RF detection and filtering

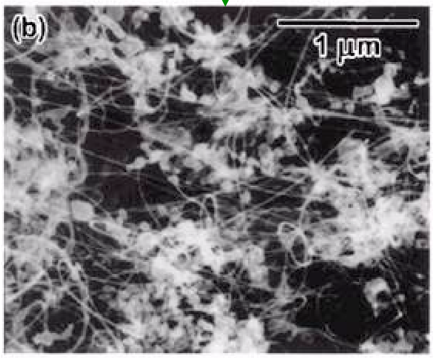
CNT fab methods and results to date

Develop a base technology for fabricating ultra-uniform, highly-ordered and electrically accessible carbon nanotube arrays for the study & device applications.

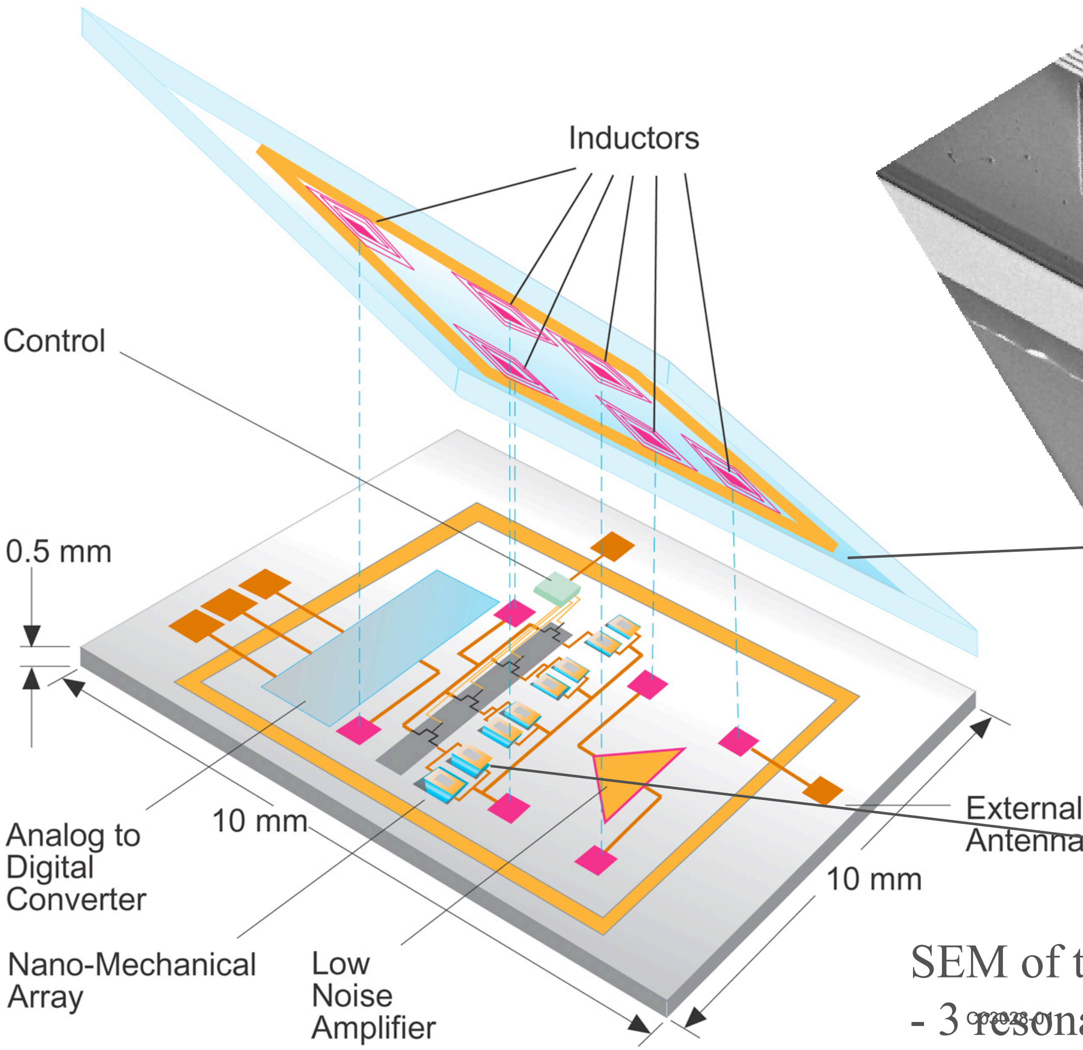


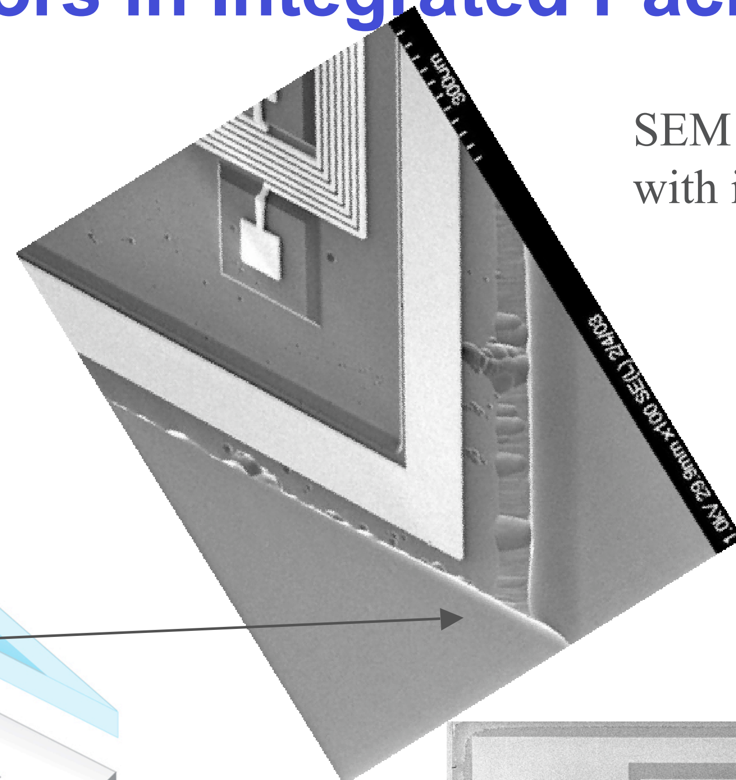
Results to date: ***excellent uniformity and ordering (95%+), as well as excellent electrical, optical and mechanic accessibility.***

As compared to the best of conventional approaches

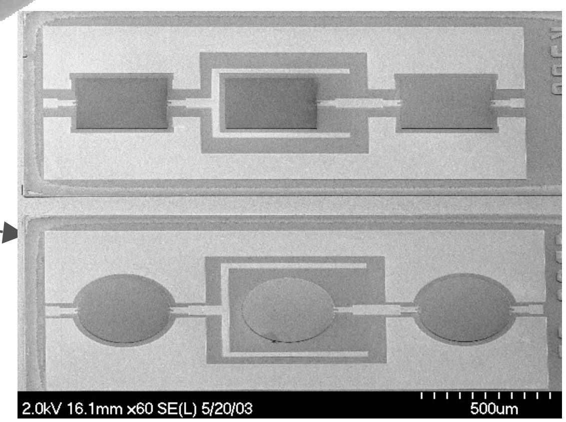


Chip in Chip Resonators in Integrated Package





SEM of package lid with inductors



SEM of two filters - 3 resonator each

C03028-01

End Slide

- DARPA NMASP Program in final phase
- High Q, nanoscale structures for RF resonators
- Nano-scale process technologies could be used in resonator fab, define gaps, coatings, etc.
- Need to think about how to get close to 50 Ohms